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A context-aware ubiquitous learning environment for conducting complex science experiments

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ABSTRACT

Context-aware ubiquitous learning (u-learning) is an innovative approach that integrates wireless, mobile, and context-awareness technologies to detect the situation of learners in the real world and provide adaptive support or guidance accordingly. In this paper, a context-aware u-learning environment is developed for guiding inexperienced researchers to practice single-crystal X-ray diffraction operations. Experimental results showed that the benefits of this innovative approach are that it is "systematic", "authentic", and "economical", which implies the potential of applying it to complex science experiments, such as physics, chemistry or biotechnology experiments, for graduate and PhD students in colleges, or research workers in research institutes.

1. Introduction

In the past decade, the rapid advance in broadband and wireless Internet technologies has promoted the utilization of wireless applications in our daily lives. In the meantime, a variety of embedded and invisible devices, as well as the corresponding software components, have been developed and connected to the Internet wirelessly. This new Internet-ready environment has been called a ubiquitous computing environment, as it enables many people to seamlessly utilize huge amounts and various kinds of "functional objects" through network connections anytime and anywhere (Minami, Morikawa, & Aoyama, 2004). Another feature of the ubiquitous computing environment is the use of wireless communication objects with sensors, so that the system can sense user information and environmental information in the real world and then provide personalized services accordingly. Such a feature is often called "context awareness" (Khedr & Karmouch, 2004; Yang, 2006).

Recently, scholars of e-learning have noticed the progress of wireless communication and sensor technologies; therefore, the research issues have progressed from web-based learning to mobile learning (Chen, Chang, & Wang, 2008), and from mobile learning to context-aware ubiquitous learning (u-learning), in which the learning system can detect students' behaviors and guide them to learn in the real world with personalized support from the digital world (Hwang, Tsai, & Yang, 2008).

Most of the previous studies concerning context-aware u-learning have been conducted on natural science courses (Chu, Hwang, Huang, & Wu, 2008; Rogers et al., 2005) or language training courses (Joiner, Nethercott, Hull, & Reid, 2006; Ogata & Yano, 2004), and have aimed to guide the students to observe real-world objects or to experience real-world contexts. Only a few studies have attempted to apply this innovative approach to simple science experiments, such as computer hardware assembly (El-Bishouty, Ogata, & Yano, 2007). Moreover, although researchers have recognized the great potential of context-aware u-learning, few practical applications have been implemented owing to the insufficient experience in developing context-aware u-learning environments and designing learning activities.

In this paper, we attempt to develop a context-aware u-learning environment to assist novice researchers in learning a complex science experiment, that is, the single-crystal X-ray diffraction procedure; moreover, an expert system has been developed to instruct the learners

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based on the contexts sensed in the real world. From the feedback of several researchers who have experienced the learning environment, it is concluded that the innovative approach can improve the learning efficiency and effectiveness of the learners.

2. Relevant research

In the past decades, researchers have demonstrated and discussed the beneficial effects of technology-enhanced learning (Hwang, 2003). Crowe and Zand (1997) indicated that the use of technology could provide a lifeline for learners who may otherwise feel too isolated and helpless in learning. They determined that the use of technology will become easier and therefore more effective; in addition, the cost of technology-enhanced learning is relatively cheap, such that many students will clearly see it as attractive in comparison with the cost of a face-to-face tutorial.

Recently, researchers further indicated several features and potential benefits of applying the context-aware u-learning approach, including the provision of more adaptive and active learning supports, the integration of real-world and digital learning scenarios, and the accomplishment of real-world practice environments with portfolio-recording functions (Chu et al., 2008; Hwang et al., 2008). In the following, several important dimensions of context-aware u-learning are introduced.

2.1. Technical aspect

To develop context-aware and seamlessly integrated Internet environments, a variety of new techniques and products concerning ubiquitous computing have been developed in recent years, such as sensors and actuators, RFID (Radio Frequency Identification) tags and readers, wireless communication, mobile phones, PDAs, and wearable computers (Feeney, Ahgre, & Westerlund, 2001; Kindberg & Fox, 2002).

From the user's point of view, in a ubiquitous computing environment, anyone can make use of computers that are embedded everywhere in a public environment at any time (Abowd, 2000; Ponnekanti, Lee, Fox, Hanrahan, & Winograd, 2001). A user equipped with a mobile device can connect to any computer and access the network using wireless communication technology (Uemukai, Hara, & Nishio, 2004). Moreover, not only can a user access the network actively, but computers around the user can recognize their behavior and offer various services according to their situation, the mobile terminal's facilities, and the network bandwidth (Beigl, Gellersen, & Schmidt, 2001; Cheng & Marsic, 2002). User assistance via ubiquitous computing technologies is realized by providing users with proper decisions or decision alternatives. That is, a ubiquitous computing technology-equipped system supplies users with timely information and relevant services by automatically sensing their various context data and effectively generating the proper results (Kwon, Yoo, & Suh, 2005).

The advent of u-computing techniques has attracted the attention of researchers from the fields of both education and computer science. In recent years, many efforts have been made to develop context-aware toolkits (Mostefaoui, Bouzid, & Hirsbrunner, 2003), which provide functionalities to enable adaptive service based on personalized contexts. In addition, several context models have been proposed to record and analyze user behaviors in the real world such that high-quality service can be provided (Isoda, Kurakake, & Nakano, 2004; Khedr, 2005; Khedr & Karmouch, 2004). For example, Isoda et al. (2004) demonstrated the use of RFID tags and floor-mounted weight sensors to detect the spatio-temporal relationship between a human user and various objects. They proposed a model for representing the user's state, in which people's activities are described in terms of time sequence aspect in addition to location aspect.

2.2. Pedagogical aspect

Researchers have indicated that students prefer "authentic activities" in which they can work with problems from the real world (Bruner, 1986; Ogata and Yano, 2004; Shaw, Turvey, & Mace, 1982; Vygotsky, 1978; Young, 1993). They have emphasized the importance of providing necessary "scaffolding" for novices to operate within the complex realistic context. Moreover, the need for the provision of supports that enable teachers to track progress, assess information, interact knowledgeably and collaboratively with individual students or cooperating groups of students, and prepare situated learning activities to assist the students in improving their ability in utilizing skills or knowledge has also been recognized (Collins, 1991; Minami et al., 2004).

Context-aware u-learning is an approach that places the students in a series of designed lessons that combine both real and virtual learning environments (Hwang et al., 2008). The connection between learner-centered and real world-situated learning has been clearly revealed in the relevant research. For example, Ogata and Yano (2004) developed a system to assist overseas students in Japan to learn Japanese. The students were conducted by the u-learning system with PDAs based on their real world locations. Moreover, Jones and Jo (2004) developed an adaptive learning environment with the ubiquitous computing technology.

Context-aware u-learning also provides an adequate environment with cognitive apprenticeships. According to Collins (1991), Collins, Brown, and Newman (1989), and Wilson and Cole (1991), the features of cognitive apprenticeships should include situated learning, coaching, scaffolding, reflection and exploration. That is, a learning system of applying cognitive apprenticeships should be situated in real-life context. Also, it should provide systematic teaching and guidance for the learners, and opportunities of practicing learning tasks as well as reviewing learning processes. The u-learning system proposed in this paper has the aforementioned features.

2.3. Benefit aspects

Context-aware u-learning is able to provide personalized and active support to assist students to learn in the real world, which is very important from both the learning attitude and the learning effectiveness aspect (Hwang et al., 2008). In recent years, several studies have reported the benefits of applying the context-aware u-learning approach, including the promotion of learning motivation (Chu et al., 2008; Ogata and Yano, 2004) and the improvement of learning effectiveness (El-Bishouty et al., 2007; Rogers et al., 2005).

For example, the study of El-Bishouty et al. (2007) on a science experiment concerning computer hardware assembly showed that 100% of the participants agreed that the learning system was helpful to them, and 67% of them were willing to recommend the system to others. Moreover, from the Ambient Wood Project (Rogers et al., 2005), which encouraged children to explore and hypothesize about different habitats found in a woodland, it was concluded that digital augmentation offers a promising way of enhancing the learning process, especially encouraging the dovetailing of exploring and reflecting when both indoors and outdoors.

For science experiments, when a student enters a lab or stands in front of an instrument, the sensors are able to detect the location of the student and transfer the information to the server. By analyzing the real time environmental/personal contexts, the profile and the on-line portfolio of individual students, the learning system is capable of guiding the students to learn in the real world by showing them the relevant information in a timely fashion, such as the operating procedure for each device, the need-to-know rules for working in the lab, and emergency handling procedures. Therefore, several benefits of applying the context-aware u-learning approach to science experiments can be expected, including the provision of more opportunities for practicing and the saving of manpower in assisting and monitoring the learners.

3. Problem description

To demonstrate the effectiveness of the innovative approach, our experiment is conducted on a well-known experiment, single-crystal X-ray structure determination. In the following subsections, the procedure of single-crystal X-ray structure determination and the problems encountered in this complex experiment are addressed in detail.

3.1. Objectives of single-crystal X-ray structure determination

Among the existing experiments of Chemical and Material Sciences, single-crystal X-ray structure determination is known to be an important experiment which provides the most convincing evidence to elucidate the three-dimensional structure of crystalline solids such as porous materials. Such a technique is very useful to researchers in analyzing the features and potentials of the materials because the synthesis of novel materials with unprecedented functionalities to fabricate numbers of devices has been one of the most important and challenging issues all over the world in the past decade. Therefore, X-ray diffraction has become a must-learn technique which assists researchers in obtaining the atomic coordinates, bond lengths, bond angles and arrangement of atoms in nano-scale from single-crystal X-ray data.

Properties and functionalities of materials can be extensively applied after the structures have been determined. Those materials which form single crystals in a size range of 0.05–0.5 mm are suitable for single-crystal X-ray diffraction. Zeolitic materials (Hung, Wang, Chen, Chang, & Lii, 2005; Hung, Wang, Chen, & Lii, 2006) and metal-organic frameworks (Lu, Su, Lu, Jiang, & Chen, 2006), which have wide applications in catalysis, separation, gas storage and molecular recognition, have usually been structurally determined by single-crystal X-ray diffraction.

3.2. Procedure of single-crystal X-ray structure determination

The single-crystal X-ray diffraction procedure consists of three phases, that is, product examination using a microscope, X-ray diffractometer operations, and structural determination using a specialized program, each of which is stated in detail below:

(1) Select a crystal of good quality and suitable size through an optical microscope and mount the crystal on the top of the glass fiber fixed in the brass pin. The usual quality criteria include transparency and morphology.
(2) Analyze the crystal by operating the X-ray diffractometer to find the cell constants within acceptable deviation. This phase is very complicated since there are many rules to be followed with various parameters to be considered.
(3) Structural determination using the specialized program to find out the three-dimensional structure of crystalline solid, such as medicines, materials and minerals. The outputs of the program include the shape, the exact distance between atoms, and other parameters for describing the structure. In this phase, the researcher needs to determine several parameters to initialize the software, including the X-ray exposure time, the voltage (from 20 kV to 50 kV) and the current (from 5 mA to 35 mA). In addition, the cell constants of the crystal need to be specified as well.

In each phase, the researchers need to be aware of the very detailed knowledge concerning material analysis as well as the operational procedure of the single-crystal X-ray diffractometer and the specialized program. Usually it will take 2–3 h to complete the three phases. However, if the researcher is not familiar with the operation of the equipment or the experimental details, longer experiment time might be needed. Equipment maintenance cost is another consideration; for example, improper operations are likely to cause damage to the single-crystal X-ray diffractometer, which is very expensive (about 200,000 USD). Moreover, part of the operations could be dangerous if inappropriate operations are carried out on the equipment, such as setting incorrect currents and voltages, or forgetting to reset the equipment to the idle state after the experiment; therefore, for an inexperienced researcher, the assistance of an experienced researcher is usually needed.

3.3. Problems to be coped with

The past experiences of many researchers not only recognize the effectiveness of single-crystal X-ray diffraction in analyzing new materials, but also reveal several difficulties applying it (Hung et al., 2005). The major difficulty is owing to the lack of well-trained researchers who are knowledgeable in material analysis and single-crystal X-ray diffractometer operations.

Usually a three-to-six month one-to-one training period is needed for a new researcher; moreover, an experienced researcher is asked to accompany the novice, which is not only time-consuming but also a waste of manpower. Novice researchers usually have difficulties in fully understanding the finer details (such as each step for picking up feasible single crystal, the setting of correct parameters for single crystals with different properties, and each step for operating the structure-analysis software) of this complex experiment procedure owing to their lack of practice. To sum up, the following barriers and difficulties are frequently encountered in training novice researchers with the existing training procedure of single-crystal X-ray diffraction:

(1) The opportunities for practice are insufficient, and hence the time needed to fully understand the experiment procedure is long.
(2) The chance of making mistakes during the experiment procedure is high. For example, in operating the X-ray diffractometer, it is difficult for novice to align the crystal in the correct position and determine the correct angle of the goniometer.
(3) The time needed to solve the problems encountered during the experiment procedure is long.

Under such circumstances, the cost of both manpower and of making mistakes could be very high. To cope with these problems, a context-aware u-learning environment has been developed, which includes an expert system to assist the learners to check each step for operating the single-crystal X-ray diffraction procedure in the real world and give suggestions to the learners based on the inference rules provided by the experienced researchers. In the following sections, the details of the u-learning environment are presented.

4. Context-aware u-learning environment for conducting complex experimental procedures

To more efficiently and effectively train the novice researchers for experimental knowledge and operational procedure, a context-aware u-learning environment has been developed with RFID and wireless communication techniques, as shown in Fig. 1. The u-learning environment consists of an instructional expert system, a learning portfolio database and a tutoring-strategy knowledge base. In the following subsections, each component of the u-learning environment is introduced in detail by taking the single-crystal X-ray diffraction procedure as the illustrative example.

4.1. Learning portfolio database

To adaptively and actively instruct the students to learn in the u-learning environment, it is necessary to define the parameters needed during the learning process. In this study, five categories of parameters are taken into consideration in developing the learning portfolio database, as shown in Hwang et al. (2008) (see Table 1).

The parameters for "Context of the learner" can be obtained via the sensors settled in the u-learning environment, which are useful for the u-learning system to identify the behaviors of each learner in the real world; the temperature parameter for "Context of the learning

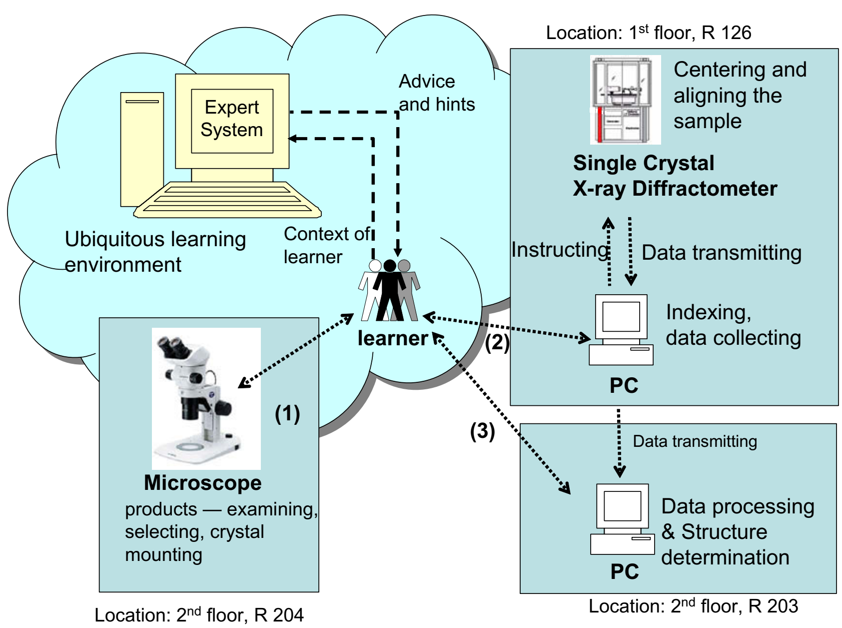

Fig. 1. Context-aware u-learning environment for single-crystal X-ray diffraction.

Table 1
Five categories of parameters in learning portfolio database.

Categories of context-aware u-learning parameters	Description of the categories
Context of the learner	Including the learner's location and arrival time
Context of the learning environment	Including the location of each sensor, the environmental temperature and the humidity of the specified location
Learner's feedback from the mobile device	Including answers to the questions asked by the system (e.g., the test of prerequisite knowledge for operating the equipment)
Learner's profile and on-line behaviors	Including personal background, on-line records (browsing, discussing), past experiences of operating the equipment and the personal learning schedule of each student
Environmental data	Including the details of the learning environment, such as the learning activities scheduled in the location, the equipment available in the location, the rules for using the environment and details of the manager (contact information) of the environment

environment" can be used by the u-learning system for determining whether the equipment currently operated by the learner is safe at the sensed environmental temperature, and will guide or warn the learner accordingly; the parameters for "Learner's feedback from the mobile device" provide important information for the expert system to determine the next learning activity for an individual student (e.g., if a

Table 2
Categories of rules in the knowledge base.

C1: Rules for "Select a crystal through an optical microscope"

R01: IF Location (student) = Location (R204)
THEN Phase (student) = "Selecting a crystal"

R02: IF Phase (student) = "Selecting a crystal" AND Location (student) = Location (R204.Microscop)
THEN Inquiry "Selecting crystals by transparency"

R03: IF Phase (student) = "Selecting a crystal" AND "Quality of selected crystal is good" = TRUE
THEN Phase (student) "Limit the size of crystal"

R04: IF Phase (student) = "Limit size of crystal" AND Location (student) = Location (R204.Microscop)
THEN Inquiry "Limit size of crystal <0.5 mm^3"

R05: IF Phase (student) = "Limit size of crystal" AND Crystal size <0.5 mm^3
THEN Phase (student) "Fix the crystal"

R06: IF Phase (student) = "Fix the crystal" AND Location (student) = Location (R204)
THEN Inquiry "Cut the fiber size to 0.5 cm"

R07: IF Phase (student) = "Fix the crystal" AND Fiber size = 0.5 cm AND Location (student) = Location (R204)
THEN Inquiry = "Fix crystal on the fiber"

R08: IF Phase (student) = "Fix the crystal" AND "Crystal fixed on fiber" = TRUE AND Location (student)! = Location (R126)
THEN Inquiry "Move to R126" and Phase (student) = "Operating the X-ray diffractometer"

C2: Rules for "Analyze the crystal by operating the X-ray diffractometer"

R01: IF Phase (student) = "Operating the X-ray diffractometer" AND Location (student) = Location (R126) AND Temperature >25 °C
THEN Next step = "Halt the operation" and Message = "Temperature warning"

R02: IF Phase (student) = "Operating the X-ray diffractometer" AND Location (student) = Location (R126) AND Temperature ⩽25 °C
THEN Inquiry "Mount and centralize the crystal"

R03: IF Phase (student) = "Operating the X-ray diffractometer" AND Location (student) = Location (R126) AND Temperature ⩽25 °C AND "Crystal mounted and in the central" = TRUE
THEN Inquiry "Check voltage = 50 kV and Current volume = 30 mA"

R04: IF Phase (student) = "Operating the X-ray diffractometer" AND Location (student) = Location (R126) AND Temperature ⩽25 °C AND "No diffraction spot" is TRUE
THEN Inquiry "Check voltage = 50 kV and Current volume = 30 mA"

R05: IF Phase (student) = "Operating the X-ray diffractometer" AND Temperature <25 °C AND Voltage = 50 kV and Current volume = 30 mA AND "No diffraction spot" is TRUE
THEN Inquiry "Check the shutter of X-ray tube"

R06: IF Phase (student) = "Operating the X-ray diffractometer" AND Temperature ⩽25 °C AND "No diffraction spot" = TRUE
THEN Inquiry "Check voltage = 50 kV and Current volume = 30 mA"

R07: IF Phase (student) = "Operating the X-ray diffractometer" AND Temperature <25 °C AND Voltage = 50 kV and Current volume = 30 mA AND "No diffraction spot" is TRUE
THEN Inquiry "check the shutter of X-ray tube"

R08: Phase (student) = "Operating the X-ray diffractometer" AND Temperature <25 °C AND Voltage = 50 kV and Current = 30 mA AND The shutter of X-ray tube working AND "No diffraction spot" = TRUE
THEN Message = "The sample might be amorphous and resembling is needed"

R09: Phase (student) = "Operating the X-ray diffractometer" AND Temperature <25 °C AND Voltage = 50 kV and Current = 30 mA AND "Shutter of X-ray tube working" = TRUE AND "No diffraction spot" = TRUE
THEN Message = "The sample might be amorphous and resembling is needed"

R10: Phase (student) = "Operating the X-ray diffractometer" AND "Has diffraction spots" = TRUE
THEN Phase (student) = "Idle the X-ray diffractometer"

R11: Phase (student) = "Idle the X-ray diffractometer" AND "Has diffraction spots" = TRUE
THEN Inquiry "Check voltage = 20 kV and Current volume = 5 mA", Phase (student) = "Collect lattice constant"

R12: Phase (student) = "Collect lattice constant" AND Voltage = 20 kV AND Current volume = 5 mA
THEN Message = "Use MATRIX to collect lattice constant"

R13: Phase (student) = "Collect lattice constant" AND "Lattice constant collect complete" = TRUE
THEN Phase (student) = "Determine lattice constant"

R14: Phase (student) = "Determine lattice constant" AND *H*,*K*,*L* >50 AND Standard deviation <0.05 AND Exist any spots strong >244
THEN Message = "Lattice constant is good", ResultL02 = "Good lattice constant", Phase (student) = "Analyze the crystal structure", Inquiry "Move to R203"

R15: Phase (student) = "Determine lattice constant" AND (*H*,*K*,*L* <50 OR Standard deviation <0.05 OR "No any spot with strength >244" is TRUE
THEN Message = "Lattice constant not good enough, re-select a crystal and diffract again", ResultL02 = "Lattice constant not good enough", Phase (student) = "Selecting a crystal", Inquiry "Move to R204"

C3: Rules for "Structural determination using the specialized program"

R01: IF Phase (student) = "Analyze the crystal structure" AND ResultL02 = "Good lattice constant" AND Location (student)! = Location (R203)THEN Message = "Move to R203"

R02: IF Phase (student) = "Analyze the crystal structure" AND Location (student) = Location (R203)
THEN Message = "Use SAINT to integral and use SHELXTL to analyze structural"

R03: IF Phase (student) = "Analyze the crystal structure" AND Location (student) = Location (R203) AND "Analyze complete" = TRUE
THEN Phase (student) = "Evaluate the structure"

R04: IF Phase (student) = "Evaluate the structure" AND Location (student) = Location (R203) AND ($15 \leqq I/\mathrm{sig} \leqq 20$) AND Max. transmission ≧0.95 AND $R1 \leqq 0.05$ AND $wR2 \leqq 2.5*(\mathrm{R1})$ AND Data completeness >95% AND Goodness-of-fit near 1 AND $R(\mathrm{int}) \leqq 0.05$
THEN Message = "Congratulation! Observe a new structure", Phase (student) = "Analysis is complete/A new structure found"

R05: IF Phase (student) = "Evaluate the structure" AND Location (student) = Location (R203) AND NOT ($15 \leqq I/\mathrm{sig} \leqq 20$) AND Max. transmission ≦0.95 AND $R(\mathrm{int}) > 0.05$
THEN Message = "Not a new structure, re-diffract current crystal or choose another sample", Phase (student) = "Analysis is complete/Not a new structure"

R06: IF Phase (student) = "Evaluate the structure" AND Location (student) = Location (R203) AND ($15 \leqq I/\mathrm{sig} \leqq 20$) AND Max. transmission ≧0.95 AND $R1 \leqq 0.05$ AND NOT ($wR2 \leqq 2.5*(\mathrm{R1})$ OR Data completeness >95% OR Goodness-of-fit near 1 OR $R(\mathrm{int}) \leqq 0.05$)
THEN Message = Reference values + "Possibly not a new structure, re-diffract again or choose another sample", Phase (student) = "Analysis is complete/Not a new structure"

student answers a question concerning the shape and size of the compound material currently observed, the u-learning system can determine whether the selected crystal is suitable for further analysis, or the step for selecting a good quality crystal needs to be re-done); the parameters for "Learner's profile and on-line behaviors" provide important information for the expert system to determine an adaptive guiding strategy for each student (e.g., for a student without sufficient experience and background knowledge to operate the equipment, a strict scaffold will be prepared to guide the student with more assistance); the parameters for "Environmental data" are stored in the database of the server, which are very useful for the u-learning system to determine what environmental resources are currently available and what learning activities can be conducted in that environment.

4.2. Instructional expert system

In the past decades, the technology used in knowledge-based systems (expert systems) has progressed from providing impressive academic results to promising commercial applications, and has thus attracted great interest and acceptance from industries. An expert system is a computer system that makes inferences based upon expert knowledge (Giarratano & Riley, 2004). In this study, the expert system approach has the following benefits over employing traditional analytical computer programs:

(1) It makes instructional decisions based on the knowledge or experiences provided by domain experts or experienced researchers; that is, the system can be easily adapted to meet new equipment or new operational concepts by modifying the knowledge base.
(2) An expert system reasons on the basis of symbolic manipulation. It knows a fact because there is a symbolic representation or a Boolean expression that defines objects and the relationships among the objects. That is, the knowledge or experiences are represented in a highly readable and easy-to-maintain way.
(3) It applies expert rules in an efficient manner in order to reach acceptable recommendations, even though the knowledge base is not complete (under construction). This feature is very important to the instructions of single-crystal X-ray diffraction since there have been new equipment or knowledge proposed by researchers all over the world; that is, it is possible that the knowledge base will require constant modification.
(4) An expert system provides justification or explanation for the processes of reasoning that lead to a conclusion, which is important for educational purposes.

The expert system approach has been applied to many problem-solving activities such as decision making, designing, planning, monitoring, diagnosing, and training activities. Subject domains that are supported by expert systems include bioengineering, defense, education, engineering, finance, and medical diagnosis (Hwang, Chen, Hwang, & Chu, 2006; Kadijevich, 1999).

In this study, the expert system plays the role of a domain expert who is experienced in single-crystal X-ray structure determination. The relevant knowledge and experiences of single-crystal X-ray structure determination are provided by the expert, and are stored in the tutoring-strategy knowledge base with specified symbolic representations.

4.3. Tutoring-strategy knowledge base

The tutoring-strategy knowledge base consists of a set of IF–THEN rules, which will be triggered by an inference engine if the predicates in the IF-part match the current learning status of the learner. A summary of the rules in the knowledge base is given in Table 2, which contains three categories of rules; that is, "C1: Select a crystal through an optical microscope", "C2: Analyze the crystal by operating the X-ray diffractometer", and "C3: Structural determination using the specialized program".

Take the rules in C2 for example; these rules are used to guide the students to analyze the crystal by operating the X-ray diffractometer. Two conditions need to be satisfied for activating this rule, that is, the location of the student must be close enough to the X-ray diffractometer, and the schedule of the student is to operate the X-ray diffractometer. Note that the location of the student is obtained via the RFID readers.

Rule R01 of C2 defines the premise for stopping the X-ray diffractometer operation based on two conditions: first, the student is currently operating the X-ray diffractometer in room R126; second, the environmental temperature is higher than 25 °C. The inference engine of the expert system will check if both conditions are satisfied, and then decide whether the actions "Halt the operation" and "Send temperature warning message" need to be taken. Rules R02 and R03 are used to guide the student to put the crystal in the proper location if the environmental temperature is acceptable.

Rule R04 of C2 defines the unsuccessful X-ray diffractometer operation based on three conditions: first, the student is currently operating the X-ray diffractometer; second, the environmental temperature is less than or equal to 25 °C; third, there is no diffraction spot found during the current operation. If all of these three conditions are satisfied, the expert system will ask the student to confirm if the voltage is equal to 50 kV and current volume is equal to 30 mA before making further decisions.

Rule R05 of C2 defines the unsuccessful X-ray diffractometer operation when the voltage is already equal to 50 kV and current volume is equal to 30 mA. If all of the five conditions are satisfied, the expert system will ask the student to confirm whether the shutter of the X-ray tube is correctly placed.

Rule R06 of C2 defines the unsuccessful X-ray diffractometer operation when the voltage is already equal to 50 kV, current volume is equal to 30 mA and the shutter of the X-ray tube is working correctly. If all of the five conditions are satisfied, the expert system will conclude that the sample might be amorphous, and then ask the student to perform the synthesizing process again.

5. Experiment and analysis

To evaluate the effectiveness of our innovative approach, the context-aware u-learning environment was installed in the chemistry building of a university. Three experienced researchers and five inexperienced researchers were asked to experience the use of the learning system to evaluate the effectiveness of the innovative approach.

5.1. Learning environment and scenarios

Fig. 2 shows the layout of the u-learning environment, which consists of three laboratories on two floors for single-crystal X-ray diffraction studies. On the first floor, there is one lab (R126) equipped with the X-ray diffractometer; on the second floor, there are one lab (R204) equipped with microscopes and one lab (R203) equipped with personal computers for structural determination.

Several RFID tags are installed in the labs and the aisles to detect the movement of the learners. Each learner is equipped with a PDA on which an RFID reader is plugged. In accordance with the learner's contexts (e.g., locations) and the environmental contexts (e.g., room temperature) sensed by the reader, the PDA is able to actively present instructional content retrieved from the server via the wireless network. Initially, the student will be guided to move toward lab R204, which is equipped with microscopes. Once the student moves close enough to the microscope, the expert system will identify the status of the student as "Crystal selecting", and hence the procedure for instructing the student to select a crystal of good quality and suitable size through the optical microscope will be presented. Furthermore, the rules that are relevant to this status will be activated according to the interacting results of the expert system and the student, as shown in Fig. 3.

Once the expert system concludes that the crystal is of good quality and a suitable size, the u-learning system will guide the student to lab R126, which is equipped with the X-ray diffractometer, and will then transform the learning phase to "operating the X-ray diffractometer". Fig. 4 depicts the scenario of a learner who is operating the X-ray diffractometer with the assistance of the u-learning system, which

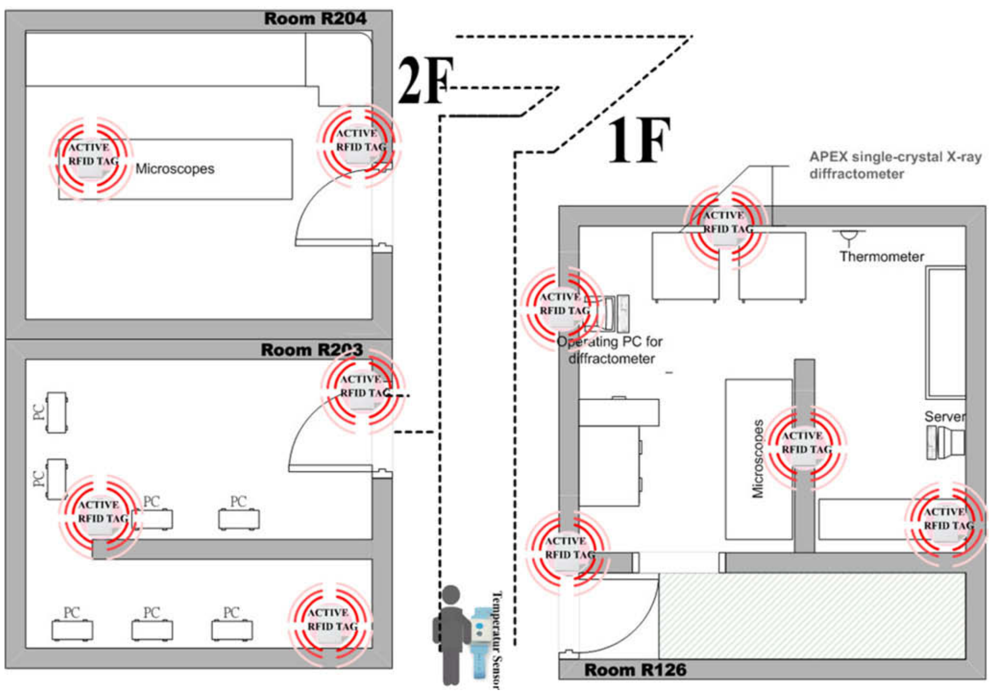

Fig. 2. Layout of the u-learning environment for single-crystal X-ray diffraction.

Fig. 3. Illustrative example of guiding the researcher to learn in the "Crystal selecting" phase.

Fig. 4. Illustrative example of guiding the researcher to operate the X-ray diffractometer and the structural analysis software.

shows the instructional content and the learning guidance via the PDA. When the expert system confirms that the ‘‘operating the X-ray diffractometer” phase is completed, the u-learning system will guide the student to lab R203, which is equipped with personal computers, to proceed with the structural determination phase.

5.2. Participants and experimental procedure

In order to have a better understanding of learners’ learning efficiency and effectiveness in the context-aware u-learning environment for single-crystal X-ray diffraction, two stages were included in the experiment.

In the first stage, three experienced researchers were chosen to take part in independent semi-structured interviews with one of the authors. Researcher A (RA) was a 30-year-old Ph.D. who had six to seven years experience conducting single-crystal X-ray diffraction, Researcher B (RB) was a 28-year-old Ph.D. who had five to six years experience, and Researcher C (RC) was a 26-year-old Ph.D. student who had only two years experience. The first stage of the experiment was conducted from January 25 to May 30, 2007.

In the second stage, five researchers (including one 25-year-old Ph.D. student, three 24-years-old graduate students and one 24-years-old graduate student) who had 6 months experience conducting the experiment were chosen for independent semi-structured interviews. The feedback of them was used to summarize the effectiveness of training using a traditional approach. In the meantime, five inexperienced researchers (22-years-old graduate student) were asked to learn the experiment procedure with the context-aware u-learning approach. The system logs of the inexperienced users were adopted in analyzing the effectiveness of the innovative approach. The second stage was conducted from November 5 to December 25, 2008.

5.3. Findings

Table 3 shows the summary of the responses of the three experienced researchers to the context-aware u-learning environment. When asked about the differences between the u-learning system environment and the one-to-one training process, it was found that the three interviewed researchers shared a consistent point of view, that is, that they considered the benefits of the equipment of the context-aware u-learning environment to be ‘‘systematic”, ‘‘authentic”, and ‘‘economical”.

For the ‘‘systematic” viewpoint, it was found that the three interviewed researchers all highlighted the value of the context-aware u-learning environment being systematic. They believed that this systematic learning program could increase learning efficiency owing to the provision of a user-friendly learning guidance which kept track of the learning process; in addition, such a systematic mechanism with a ‘‘memory bank” helps to protect the equipment, since the learners will be more serious and careful when operating the equipment.

As to the ‘‘authentic” perspective, RA, RB, and RC all shared the same position; that is, knowledge from authentic learning experience had its intrinsic value and the learning system behaved like a personalized tutor who guided them to learn in the real world. Thus, it could be concluded that the authentic learning environment motivated learners to learn more willingly. This finding also implies that the context-aware u-learning environment conforms to the conception of cognitive apprenticeship, which aims at teaching the problem-solving process applied by experts (Dickey, 2008; Enkenberg, 2001; Tsai, 2001, 2005, 2008; Woolley & Jarvis, 2007). Cognitive apprenticeship is an instructional model derived from the metaphor of the apprentice working under the master craftsperson in traditional societies. In the tra-

Table 3
Responses from three experienced researchers.

	Researcher RA	Researcher RB	Researcher RC
Experience	Six to seven years experience	Five to six years experience	Two years experience
Responses about "systematic" viewpoint	"Unlike the one-to-one training process by manpower, the u-learning system is much more organized, because the u-computing PDA will remind you of every detailed thing clearly and specifically" "The learner can go over the operating sequence repeatedly with the u-computing PDA instead of asking the same questions to the seniors" "The innovative system can take down the operating records and help to protect the equipment"	"With this innovative system, we can see who is hard-working and who is not. This would make the learners more serious while working with the equipment. Probably all learners can have a standard test after a completed training process"	"The PDA is able to remind the trainees of the sequence step by step, and this will make them have less pressure while learning"
Response s about "authentic" viewpoint	"Such a learning environment is so realistic that it can really assist the trainees in learning the operating procedure"	"The u-computing PDA shows every operating procedure that makes people feel like getting real things in the real world, and I think the trainees would prefer to learn with this u-computing system"	"The PDA learning environment seems so real to me. It will make the trainees feel like having a personalized tutor"
Responses about "economic" viewpoint	"If I were an experienced researcher, I would like to learn with this u-computing system sometime because of its convenience and innovative system. Besides, we can also save twice the time and manpower for training novices by practicing with this u-computing system" "The innovative system can take down the operating records and help to protect the equipment"	"Since the trainees don't need to jot down notes, they can concentrate on learning and have lots of drills. Moreover, a novice can handle the equipment properly through the u-computing system, and I think this would reduce the time for training"	"The greatest difference is that the trainees can learn independently. Whenever the trainees want to learn, they can just learn it without being accompanied by a senior. So, they can have much time for training hours, which is very important for a novice"

ditional master-apprentice model, the master typically performs a psycho-motor skill which is observed by the apprentice. The apprentice then goes on to practice the skill under guidance and help from the master. In the beginning, the apprentice is totally reliant on the master; later, the dependency decreases as the apprentice acquires the skills and knowledge for dealing with more complex and diverse tasks (Woolley & Jarvis, 2007).

In addition, there is another merit of this u-computing system, which is that it is "economical". All of the three researchers highly recommended the u-computing system as saving much time and manpower, which would, in turn, enhance learning efficiency and effectiveness.

Table 4 shows a summary of the responses of five researchers who had 6 months experience and learning logs of five inexperienced researchers. The *t*-test results showed that, in all of the aspects "Average number of experiments conducted per week", "Number of mistakes made per experiment", "Average time needed to deal with faults in an experiment", and "Time for fully understanding the operating procedure", the differences between those two groups were significant.

It should be noted that the data concerning the training using a traditional approach are fully based on the interviews with the researchers who had just learned the full experiment procedure in the past 6 months, while the data concerning the training with the innovative approach are mainly based on the system logs (e.g., operations, the parameters associated with each operations, starting time and ending time of each operation, the feedback from the learners and the suggestions given by the expert system) of the inexperienced researchers who only had basic knowledge concerning the experiment.

From Table 4, it is found that the average number of experiments conducted employing the innovative approach (i.e., eight times per week) is higher than that of the traditional approach (i.e., 1.9 times per week), which indicates that the inexperienced researchers have more chance to practice owing to the availability of the learning system. In the traditional approach, the researchers need to wait for the experienced researchers, who are usually very busy, to have available time, while, with the innovative approach, the learning system can provide assistance at any time, which conforms to the spirit of computer-supported mastery learning (Corbett & Anderson, 1992).

It is also interesting to see that the average number of mistakes made per experiment was significantly reduced when using the innovative approach. This finding conforms to the response of the experienced researcher RB who indicated that the use of the learning system would make the learners more serious while working with the equipment. In addition, as the learning system invokes the expert system to check the personal and environmental contexts and warn the learners of any potential problems immediately, it is possible that some chances of making mistakes were avoided. In addition, for the inexperienced researchers, the average time needed for dealing with the faults was shortened by using the innovative approach, since some faults were directly resolved with the guidance provided by the expert

Table 4
Summary of responses of five researchers who had 6 months experience and system logs of five inexperienced researchers.

	Traditional approach (mean, SD)	U-learning approach (mean, SD)	*t*
Average number of experiments conducted per week	1.9 (0.55)	8 (2.38)	-5.59^{**}
Number of mistakes made per experiment	2.3 (0.65)	0.32 (0.08)	6.75^{***}
Average time needed to deal with faults in an experiment (days)	2.5 (0.66)	0.45 (0.15)	6.77^{***}
Time for fully understanding the operating procedure (months)	5.5 (1.49)	2 (0.45)	5.04^{**}

** $p < .01$.
*** $p < .001$.

system. Such findings conform to the scaffolding theory, which emphasizes the provision of necessary "scaffolding" for novices to operate within the complex realistic context, but still permit experts to work within the same situation (Bruner, 1986; Demetriadis, Papadopoulos, Stamelos, & Fischer, 2008; Lee, Baik, & Charlesworth, 2006; Li & Lim, 2008; Nussbaum et al., 2009; Vygotsky, 1978).

When talking about the expected time for fully understanding the operating procedure, all of the inexperienced researchers showed their confidence in using the innovative approach. The inexperienced researchers learned most of the training units within 1.5 months, and expected to complete the full training procedure in 2 months; that is, the estimated time needed for training the inexperienced researchers with the innovative approach was 2 months, while the average time for training the researchers with traditional approach was 5.5 months.

In terms of the "cost benefit", the possible costs that can be saved include the manpower cost (the need for assistance and guidance from experienced researchers), the material cost (the need for redoing part of the experiment owing to the faults) and the cost of exhausting the equipment. Those costs are highly dependent on the number of researchers to be trained. Fig. 5 shows the estimated cost benefits for training different numbers of researchers in a year. The estimation has been made based on suggestions from the experienced researchers who need to take care of the following working items:

(1) Identifying the samples: 16 USD for each sample.
(2) Indexing the samples: 16 USD for each sample.
(3) Collecting X-ray diffraction data at room temperature: 16 USD for each sample.
(4) Collecting X-ray diffraction data at a low temperature: 35 USD for each sample.
(5) Analyzing structure of single crystal: 70 USD for each sample.
(6) Retrieving historical data: 35 USD for each request.

The average number of samples handled by each experienced researcher per month is 40, and the average number of requests for historical data is 20. Therefore, the cost benefit of easing the load of an experienced researcher is $(16 + 16 + 16 + 35 + 70) \times 40 + 35 \times 20 = 6820$ USD per month and 81,840 USD per year. As shown in Table 4, the development of the context-aware u-learning system can improve the average training efficiency by nearly three times (i.e., 5.5 months vs. 1.7 months); moreover, an experienced researcher usually spends $1.9 \times 3 = 5.7$ h training each inexperienced researcher. That is, to train 10 novices, the innovative approach will ease 3×57 h = 171 working hours for the experienced researchers who work 160 h per month. Therefore, the cost benefit of developing the system is $(171/160) \times 6820 = 7289$ USD per month for training 10 persons, which implies a cost benefit of $7289 \times 12 = 87{,}468$ USD per year. Note that the set up cost of the context-aware u-learning system is about 8000 USD.

5.4. Limitations

Although the researchers who participated in the experiment have addressed several benefits of applying the innovative approach, there are several limitations in applying this system:

(1) The u-computing system is designed to guide the researchers to learn. In case that the learners do not follow the instructions given by the system, the effects of the system will be reduced.
(2) The u-computing system makes judgments on possible mistakes or faults based on the detected information and the feedback from the learners; therefore, if the learners' feedback is incorrect or incomplete, the system will not be able to provide useful suggestions.
(3) The u-computing system highly relies on wireless networks; therefore, it can only be used in a learning environment with wireless communications.

In addition, the researchers who participated in the experiment also offered some suggestions for improvement of the u-computing system. For example, RC mentioned that "graphic illustrations" could make the u-computing PDA interface more compelling. RA thought that there should be more sensors or a larger database for the u-learning environment to develop a more integral learning system. In other words, the u-computing system must record many learning patterns based on each learner's experience. Therefore, learners should acquire new knowledge directly by undergoing the operating sequence by themselves. By the same token, RB claimed that learners should rely on the u-computing system to make their learning more adaptive.

Another problem that prevents the u-computing system from fully taking the place of the traditional approach is the limitation of the battery power. For a complex experiment, it might take several hours to complete the entire procedure; nevertheless, the battery power of

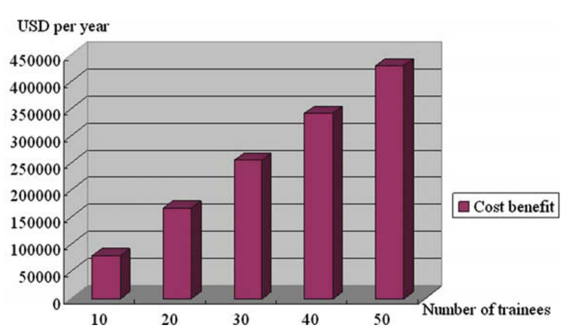

Fig. 5. Estimated cost benefit for using the context-aware u-learning approach.

the mobile device equipped with an RFID reader can only last 2 h. Fortunately, electric power technology is advancing rapidly, and hence such a problem will eventually be resolved.

6. Conclusions

In conventional e-learning environments, people learn and practice in the cyber world; that is, complex operations or problem-solving procedures are usually trained in a web-based learning environment that simulates the scenarios of the problem domain. Such a learning or training approach is helpful to the learners in identifying the problem to be coped with; nevertheless, it is almost impossible for the trainees to learn the problem-solving skills without observing and practicing in the real world. For some important courses, such as those that involve the operation of valuable equipment or have potential dangers, one-to-one instruction may be quite necessary, but it is inefficient and manpower consuming. To cope with these problems, in this study, a context-aware u-learning environment with an expert system approach is proposed, which is able to sense the personal and environmental contexts to provide adaptive supports to the learners.

The experimental results of training researchers for single-crystal X-ray diffraction operations have depicted the benefits of applying our innovative approach. All of the trainees have indicated that the benefits of the constructed context-aware u-learning environment are that it is "systematic", "authentic", and "economical". They emphasized that the u-learning system is much more organized than traditional one-to-one instruction owing to its ability to remind the trainees of every detailed point clearly and specifically, and such a systematic learning facility could increase learning efficiency. They also indicated that they would prefer to learn with such a u-learning system because of its convenience and innovative system. One trainee even indicated that almost twice the time and manpower for training novices can be saved by practicing with this u-learning system.

In conclusion, the innovative approach proposed in this study can effectively and efficiently improve the performance of training complex problem-solving skills in the real world. Researchers are encouraged to develop more related u-learning systems, and to carefully examine their impacts on student learning. In addition, the successful experience of training researchers in the procedure of single-crystal X-ray diffraction reveals the possibility of applying the innovative approach to other science environments, such as specific physics or chemistry experiments. From the aspects of economics, efficiency and effectiveness, it is worth trying to develop context-aware ubiquitous learning environments for such complex experimental procedures that need to be conducted via one-to-one instructions.

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References

Abowd, G. D. (2000). Classroom 2000: An experiment with the instrumentation of a living educational environment. *IBM Systems Journal, 38*(4), 508–530.

Beigl, M., Gellersen, H.-W., & Schmidt, A. (2001). MediaCups: Experience with design and use of computer-augmented everyday objects. *Computer Networks, 35*(4), 401–409.

Bruner, J. (1986). *Actual minds, possible worlds*. Cambridge, MA: Harvard University Press.

Chen, G. D., Chang, C. K., & Wang, C. Y. (2008). Ubiquitous learning website: Scaffold learners by mobile devices with information-aware techniques. *Computers and Education, 50*, 77–79.

Cheng, L., & Marsic, I. (2002). Piecewise network awareness service for wireless/mobile pervasive computing. *Mobile Networks and Applications (MONET), 7*(4), 269–278.

Chu, H. C., Hwang, G. J., Huang, S. X., & Wu, T. T. (2008). A knowledge engineering approach to developing e-libraries for mobile learning. *The Electronic Library, 26*(3), 303–317.

Collins, M. (1991). *Adult education as vocation: A critical role for the adult educator*. New York: Routledge.

Collins, A., Brown, J. S., & Newman, S. E. (1989). Cognitive apprenticeship: Teaching the craft of reading, writing, and mathematics. In L. B. Resnick (Ed.), *Knowing, learning, and instruction: Essays in honor of Robert Glaser* (pp. 453–494). Hillsdale, NJ: Lawrence Erlbaum Associates.

Corbett, A. T., & Anderson, J. R. (1992). Student modeling and mastery learning in a computer-based programming tutor. *Lecture Notes in Computer Science, 608*, 413–420.

Crowe, D., & Zand, H. (1997). Novices entering mathematics – I. The impact of new technologies. *Computers and Education, 28*(1), 43–54.

Demetriadis, S. N., Papadopoulos, P. M., Stamelos, I. G., & Fischer, F. (2008). The effect of scaffolding students' context-generating cognitive activity in technology-enhanced case-based learning. *Computers and Education, 51*(2), 939–954.

Dickey, M. D. (2008). Integrating cognitive apprenticeship methods in a Web-based educational technology course for P-12 teacher education. *Computers and Education, 51*(2), 506–518.

El-Bishouty, M. M., Ogata, H., & Yano, Y. (2007). PERKAM: Personalized knowledge awareness map for computer supported ubiquitous learning. *Educational Technology and Society, 10*(3), 122–134.

Enkenberg, J. (2001). Instructional design and emerging models in higher education. *Computers in Human Behavior, 17*(5–6), 495–506.

Feeney, L., Ahgre, B., & Westerlund, A. (2001). Spontaneous networking: An application-oriented approach to ad hoc networking. *IEEE Communication Magazine, 39*(6), 176–181.

Giarratano, J., & Riley, G. (2004). *Expert systems: Principles and programming* (4th ed.). Boston, MA: PWS Publishing.

Hung, L. I., Wang, S. L., Chen, C. Y., Chang, B. C., & Lii, K. H. (2005). $Rb_3In(H_2O)Si_5O_{13}$: A novel indium silicate with a $CdSO_4$-topological-type structure. *Inorganic Chemistry, 44*, 2992–2994.

Hung, L. I., Wang, S. L., Chen, Y. H., & Lii, K. H. (2006). $Rb_6(InCo)_2(Si_9O_{26})$: A mixed-metal silicate containing 20-membered-ring silicate single layers with a very low Si:O ratio. *Inorganic Chemistry, 45*, 2100–2103.

Hwang, G. J. (2003). A concept map model for developing intelligent tutoring systems. *Computers & Education, 40*(3), 217–235.

Hwang, G. H., Chen, J. M., Hwang, G. J., & Chu, H. C. (2006). A time scale-oriented approach for building medical expert systems. *Expert Systems with Applications, 31*(2), 299–308.

Hwang, G. J., Tsai, C. C., & Yang, S. J. H. (2008). Criteria, strategies and research issues of context-aware ubiquitous learning. *Educational Technology and Society, 11*(1), 81–91.

Isoda, Y., Kurakake, S., & Nakano, H. (2004). *Ubiquitous sensors based human behavior modeling and recognition using a spatio-temporal representation of user states*. Paper presented at the 18th international conference on advanced information networking and application, Fukuoka, Japan, March.

Joiner, R., Nethercott, J., Hull, R., & Reid, J. (2006). Designing educational experiences using ubiquitous technology. *Computers in Human Behaviors, 22*(1), 67–76.

Jones, V., & Jo, J. H. (2004). Ubiquitous learning environment: An adaptive teaching system using ubiquitous technology. In R. Atkinson, C. McBeath, D. Jonas-Dwyer, & R. Phillips (Eds.), *Beyond the comfort zone: Proceedings of the 21st ASCILITE conference* (pp. 468–474). Perth, 5–8 December. <http://www.ascilite.org.au/conferences/perth04/procs/jones.html>.

Kadijevich, Dj. (1999). An approach to learning mathematics through knowledge engineering. *Journal of Computer Assisted Learning, 15*(4), 291–301.

Khedr, M. (2005). *A semantic-based, context-aware approach for service-oriented infrastructures*. Paper presented at the 2nd IFIP international conference on wireless and optical communications networks (WOCN 2005), Dubai, United Arab Emirates, March.

Khedr, M., & Karmouch, A. (2004). Negotiating context information in context-aware systems. *IEEE Intelligent Systems, 19*(6), 21–29.

Kindberg, T., & Fox, A. (2002). System software for ubiquitous computing. *IEEE Pervasive Computing, 1*(1), 70–81.

Kwon, O., Yoo, K., & Suh, E. (2005). *ubiES: An intelligent expert system for proactive services deploying ubiquitous computing technologies*. Paper presented at the 38th Hawaii international conference on system sciences, Hawaii, USA, January.

Lee, Y. S., Baik, J., & Charlesworth, R. (2006). Differential effects of kindergarten teacher's beliefs about developmentally appropriate practice on their use of scaffolding following inservice training. *Teaching and Teacher Education, 22*(7), 935–945.

Li, D. D., & Lim, C. P. (2008). Scaffolding online historical inquiry tasks: A case study of two secondary school classrooms. *Computers and Education, 50*(4), 1394–1410.

Lu, W. G., Su, C. Y., Lu, T. B., Jiang, L., & Chen, J. M. (2006). Two stable 3D metal-organic frameworks constructed by nanoscale cages via sharing the single-layer walls. *Journal the American Chemical Society, 128*, 34–35.

Minami, M., Morikawa, H., & Aoyama, T. (2004). *The design of naming-based service composition system for ubiquitous computing applications*. Paper presented at the 2004 international symposium on applications and the internet workshops, Tokyo, Japan, January.

Mostefaoui, S. K., Bouzid, A. T., & Hirsbrunner, B. (2003). *Using context information for service discovery and composition.* Paper presented at the 5th international conference on information integration and web-based applications and services (IIWAS 2003), Jakarta, Indonesia, September.

Nussbaum, M., Alvarez, C., McFarlane, A., Gomez, F., Claro, S., & Radovic, D. (2009). Technology as small group face-to-face collaborative scaffolding. *Computers and Education, 52*(1), 147–153.

Ogata, H., & Yano, Y. (2004). *Context-aware support for computer-supported ubiquitous learning*. Paper presented at the 2nd IEEE international workshop on wireless and mobile technologies in education, JhongLi, Taiwan, March.

Ponnekanti, S. R., Lee, B., Fox, A., Hanrahan, P., & Winograd, T. (2001). ICrafter: A service framework for ubiquitous computing environments. In *Proceeding of 2001 international ubiquitous computing conference (Ubicomp 2001)* (pp. 56–75). Berlin: Springer-Verlag Press.

Rogers, Y., Price, S., Randell, C., Fraser, D. S., Weal, M., & Fitzpatrick, G. (2005). Ubi-learning integrating indoor and outdoor learning experiences. *Communications of the ACM, 48*(1), 55–59.

Shaw, R., Turvey, M. T., & Mace, W. (1982). Ecological psychology: The consequence of a commitment to realism. In W. B. Weimer & D. S. Palermo (Eds.), *Cognition and the symbolic processes* (pp. 159–226). Hillsdale, NJ: Lawrence Erlbaum.

Tsai, C.-C. (2001). The interpretation construction design model for teaching science and its applications to Internet-based instruction in Taiwan. *International Journal of Educational Development, 21*, 401–415.

Tsai, C.-C. (2005). Preferences toward Internet-based learning environments: High school students' perspectives for science learning. *Educational Technology & Society, 8*(2), 203–213.

Tsai, C.-C. (2008). The preferences toward constructivist Internet-based learning environments among university students in Taiwan. *Computers in Human Behavior, 24*, 16–31.

Uemukai, T., Hara, T., & Nishio, S. (2004). *A method for selecting output data from ubiquitous terminals in a ubiquitous computing environment*. Paper presented at the meeting of proceedings of the 24th international conference on distributed computing systems workshops (ICDCSW'04), Tokyo, Japan, March.

Vygotsky, L. (1978). *Mind in society: The development of higher psychological process*. Cambridge, MA: Harvard University Press.

Wilson, B., & Cole, P. (1991). A review of cognitive teaching models. *Educational Technology Research and Development, 39*(4), 47–64.

Woolley, N. N., & Jarvis, Y. (2007). Situated cognition and cognitive apprenticeship: A model for teaching and learning clinical skills in a technologically rich and authentic learning environment. *Nurse Education Today, 27*(1), 73–79.

Yang, S. J. H. (2006). Context aware ubiquitous learning environments for peer-to-peer collaborative learning. *Educational Technology and Society, 9*(1), 188–201.

Young, M. F. (1993). Instructional design for situated learning. *Educational Technology Research and Development, 43*(1), 43–58.