A Unified Framework for Augmented Reality and Knowledge-based Systems in Maintaining Aircraft

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Abstract

Aircraft maintenance and training play one of the most important roles in ensuring flight safety. The maintenance process usually involves massive numbers of components and substantial procedural knowledge of maintenance procedures. Maintenance tasks require technicians to follow rigorous procedures to prevent operational errors in the maintenance process. In addition, the maintenance time is a cost-sensitive issue for airlines. This paper proposes intelligent augmented reality (IAR) system to minimize operation errors and time-related costs and help aircraft technicians cope with complex tasks by using an intuitive UI/UX interface for their maintenance tasks. The IAR system is composed mainly of three major modules: 1) the AR module 2) the knowledge-based system (KBS) module 3) a unified platform with an integrated UI/UX module between the AR and KBS modules. The AR module addresses vision-based tracking, annotation, and recognition. The KBS module deals with ontology-based resources and context management. Overall testing of the IAR system is conducted at Korea Air Lines (KAL) hangars. Tasks involving the removal and installation of pitch trimmers in landing gear are selected for benchmarking purposes, and according to the results, the proposed IAR system can help technicians to be more effective and accurate in performing their maintenance tasks.

Introduction

Given the increasingly complex nature of maintenance operations in the aerospace field, handling huge numbers of technical documents for maintenance has become a tedious process (Zhu et al. 2012). Figure 1 shows the current workplace environment. Maintenance procedure guidelines and instructions are paper-based and created for expected aircraft configurations. Therefore, for a given task, technicians must often interpret such written instructions or procedures and adapt them to the actual configuration (Henderson and Feiner 2011). Here some ambiguity may arise when workers translate instructions and procedures into actions and activities (Fox 2010).

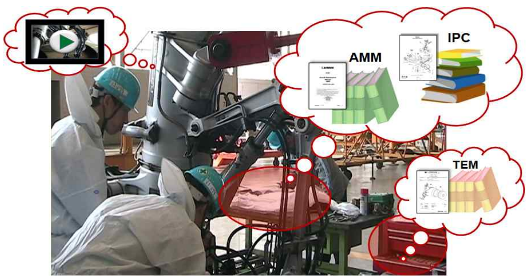

Figure 1: Current Workplace Environment

Effective and efficient aircraft maintenance plays a critical role in sustaining the safe performance of machinery for quality of aircraft maintenance and training effectiveness. For this, the Intelligent Augmented Reality (IAR) R&D project has been conducted to apply IAR concepts to aircraft maintenance and personnel training.

The IAR project is part of a collaborative effort between academia and industry players. Researchers from INHA University and the University of Southern California (USC) and aircraft maintenance experts from Korean Air Lines (KAL) and Airbus have worked together on the IAR project to develop a unified framework for a system based on the augmented reality (AR) and the knowledge-based system (KBS) and validate its performance in context of aircraft maintenance. The proposed IAR system is composed mainly of three major modules: 1) the AR module 2) the KBS module 3) the UI/UX module. Some methods for determining information relevant to specific parts of an aircraft in KBS as well as those for determining ways to clearly to present information and task instructions in the context of an actual aircraft in AR have been developed.

In the KBS, the ontology technology is adopted to retrieve information relevant to maintenance tasks and maintain multiple resources related to maintenance tasks. The aircraft ontology provides a useful vocabulary for classifying a particular aircraft maintenance suite and their relationships with various activities in the aircraft domain. It also connects all resources such as maintenance manuals, figures, videos, and AR content. The proposed approach uses this ontology to address ambiguous problems and improve searches for maintenance information. Overall, these methods enhance the quality and speed of decision making by personnel in the context of aircraft maintenance procedures. In addition, the display of this information with AR display methods enhances worker comprehension and certainty, minimizing task errors.

The AR approach fuses information such as text, images, and video to images of real-world objects to ensure that the information is provided with the correct spatial context for the physical aircraft structure. AR has been pursued for many years and is widely embraced by practitioners. Its expected benefits include higher worker efficiency and accuracy for procedures. In addition, the approach leverages the increasing investment in digital models.

The R&D objectives for the IAR system can be summarized as follows:

- Develop an integrated demonstration system for selected maintenance tasks for A330 landing gear to demonstrate the benefits and capability of unifying of AR and KBS technologies.
- Research and develop novel AR-based tracking methods suitable for aircraft maintenance tasks.
- Research and develop intelligent methods for providing KBS-based instructional maintenance
- Improve the quality and speed of maintenance procedures through KBS selection and AR presentation of task instructions and guidelines.

System Description

This section describes the proposed IAR system, which consists of the AR module, the KBS module and the UI/UX module. USC has led AR module development, and INHA has led KBS module development, integration of the AR and KBS, and the UI/UX module. KAL has provided necessary domain knowledge for aircraft maintenance.

System Overview

As shown in the figure 2, all related resources are managed based on the modeled ontology. The hanger is the work-place, and technicians obtain an automatic context-aware view through the IAR system. Once the AR module detects the current workplace condition, the KBS module retrieves all relevant information with context-awareness.

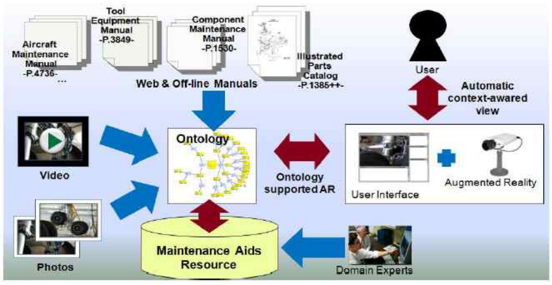

Figure 2: System Overview of the IAR system

AR Module

AR is a compelling means for findings ways to present and interact with information in context. In the IAR system, the AR module handles marker-less recognition and tracking methods needed to augment annotations with camera images. The AR module presents improved computer vision for real-time and robust performance under challenging aircraft settings. The AR module consists mainly of the Authoring tool and the AR component. The Authoring tool is used to create annotation databases, which are IAR image databases for managing images for recognizing, tracking, and translating objects. The Authoring tools include the Database Builder tool to create training databases, the Authoring Homography tool to compute geometric transformations between images in the training database, and the Annotations Editor to define and manage the augmentation of annotations and their behaviors. The Annotation Editor provides end users with the ability to annotate Key Reference Images (KRIs) by using a variety of annotation elements including static and animated images, circles, text labels, interactive buttons and hotspots.

The AR module is based on three algorithms for recognition and tracking: 1) the augmented feature (AF) algorithm to create clusters of aggregate-features with a single descriptor to speed matching, and increase the number and robustness of matches (Wang, Guan, and You 2011); 2) the self-similarity image matching (normalization within images) algorithm to create image descriptions and matching processes based on the image's internal self-similarity (Huang, You and Zhao 2011); and 3) the geometry-pixels method to treat the image matching problem as an edge or geometry matching problem (Pang and Neumann 2013). Through three algorithms, the AR component provides real-time and robust performance displaying necessary information in a given context.

KBS Module

The KBS module addresses tens of thousands pages of technical documents and relevant resources over the whole project period. Handling large numbers of technical documents for maintenance is a tedious and time-consuming process for human operators. Therefore, what matters more is to find exact information for a given task. The KBS at the heart of the IAR system is key to enabling the machine to understand the fundamental knowledge of the tasks in the maintenance document.

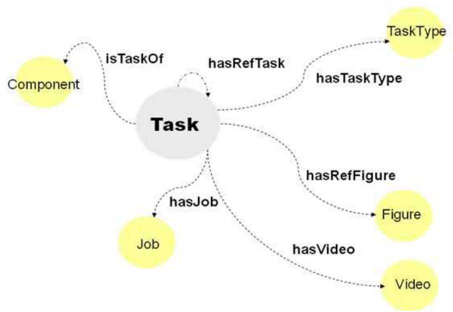

Figure 3: Relationships between the Task class and other classes

The KBS represents a means for identifying information relevant to maintenance tasks and recognizing unambiguous information in the maintenance context. The KBS module provides single-interface access to multiple information resources, and uses a unified repository of various resources for efficient ontology-oriented resource management. The KBS module discovers new knowledge inferred by facts and rules to support decision making through the preprocessing of ontology-based information. Some examples of new knowledge include 1) cross-reference information to interconnect heterogeneous manuals as a result of the fact that aircraft technical manuals employ different numbering and naming systems for components or parts at the instructional level, 2) pre-task information to comply with safety instructions, and 3) tools and multimedia information for specific instructions on given tasks. The KBS module supports a persistent ontology model; ontology-driven navigation; textual rendering of the class hierarchy; textual description of instances to allow the discovery of relationships; advanced drill-down capability and enhanced resource integration. All resources such as videos, photos and manuals are integrated by the modeled ontology. Videos are pre-recorded clips of maintenance operations by trained or professional technicians and visually depict the correct performance of tasks. Photos are collections of snapshots of actual components and parts of the aircraft. There are four types of manuals: the AMM (Aircraft Maintenance Manual), the TEM (Tool Equipment Manual), the CMM (Component Maintenance Manual) and the IPC (Illustrated Parts Catalog). This ontology-driven resource integration ensures the effective deployment of the IAR to provide technicians with absolutely clear and precise guidelines for performing critical tasks.

The ontology, modeled and updated over the whole project period, is an important component for the KBS module in that it is responsible for managing consistent information and providing essential information. Domain knowledge was obtained from maintenance practitioners during the first six months after the start-up. In addition, technical manuals such as AMMs and CMMs were analyzed to determine how instructions can be displayed in the AR environment. The ontology of an IAR project follows the OWL-DL standard and consists of 56 classes, 17 data properties, and 40 relationships between classes if we are considering tasks involving the removal and installation of pitch trimmers in landing gear. The ontology is modeled by using Protégé which is an open-source ontology editor and framework for building intelligent systems. Figure 3 provides an example of the core relationships between the Task class and other classes. Classes Task and Job are connected by the *hasJob* relationship because a task is composed of several jobs. To provide multimedia resources such as figures and videos, *hasRefFigure* and *hasVideo* relationships are modeled. A task treats a component through its procedure, and a relationship between the Classes Task and Component is specified as *isTaskOf* relation.

The generation of an ontology instance is performed based on the modeled ontology schema. The ontology population toolkit (OPT) is built to generate ontology instances. In the preprocessing phase, raw AMM data in SGML format are converted into a well-formed XML schema. The OPT then creates instances based on the ontology schema and rules. These rules are also used to map the well-formed XML schema into the ontology schema. Instance validation and inference process are performed using the JENA engine. The inference process is based on the ontology schema and instances. For example, instances of the Subtask class have relationships between the instances through relations *followedAfter* and *precededBy*. Two relations are defined as the inverse property. If an instance "Subtask 32-11-15-420-050" has *followedAfter* relation with "Subtask 32-11-15-870-050", then the inference module of the OPT generates an inferred fact that the instance "Subtask 32-11-15-870-050" has a *precededBy* relation with "Subtask 32-11-15-420-050". Inferred triples are saved to the triple repository. The OPT also provides an enhanced video annotation function with semantics in which the user can set start and end times of a given video clip with timelines for each instruction. Other details of the ontology and OPT processes are described in (Ha et al. 2011). The AMM for the A330 aircraft consists of 61K pages covering 8K tasks in 46 chapters. All ontology instances generated and inferred from the OPT process by using all tasks include 38,673K triples. Because of the importance of delivering each instruction and corresponding information on tools and parts during the maintenance process for an aircraft, the OPT extracts this information from each instruction. Contextual information such as different views from different manuals and different structural drawings is automatically maintained and updated in different windows for maintenance engineers as they navigate one instruction after another through the support of AR. 11 judges participated in evaluation and validation of generated ontology instances to compare with actual manuals. After the evaluation and validation, the OPT module was updated and errors in generated ontology instances were corrected.

UI/UX of the IAR System

Domain knowledge was obtained from maintenance practitioners during the first six months after the start-up. After the knowledge acquisition from the practitioners and manuals, it took another two years to complete IAR system. By analyzing how they use different manuals in many different perspectives during maintenance work, we successfully designed the UI/UX to reflect engineers' knowledge and experience in their maintenance work.

The UI/UX module is also designed to communicate with the KBS and AR modules by integrating message communication techniques to handle various events occurring through user interactions. The UI/UX module consists of several small windows and tab controls. A snapshot of the UI/UX module is shown in Figure 4.

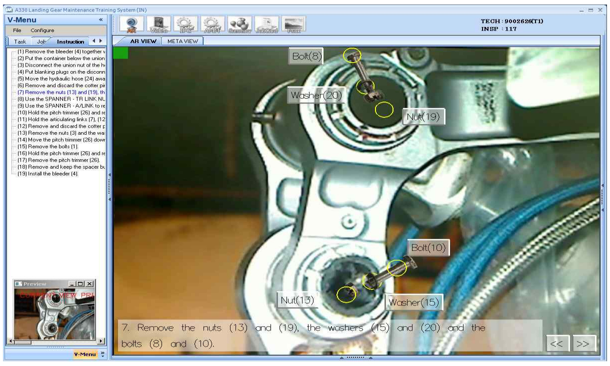

Figure 4: UI/UX

The ontology-based tree also includes several tabs, including Component, Task, Job and Instruction. The ontology-based tree is built on the created ontology and is used for later context management. AR view is integrated to provide the AR and is in a central display area called main view of GUI. The AR module is integrated with AR view in the IAR system. AR view displays the content of any sub-window when the user clicks a sub-window tab such as Video view, IPC view, AMM view, Instruction Summary view, or Job Card view. Each view shows specific content to the user in the current context.

Integration

Existing AR-based systems for aircraft maintenance generally tie a single instruction to a specific scene with augmented objects, which can be a very difficult vision problem if the technician is dealing with instructions for many different jobs derived from the problem of distinguishing one scene from another similar scene across different tasks. To address this problem, the KBS approach provides technicians with context-supported instructions for a given task. The IAR system interconnects heterogeneous manuals and resources such as the TEM and the instructional level of the maintenance process in the AMM. By unifying the AR and KBS modules based on the established ontology, the IAR system provides semantic interoperability between all resources related to aircraft maintenance and many types of technical documents. Through the modeled ontology, all information in various manuals and external resources such as figures and videos is interlinked. In addition, when augmented objects are created by the Annotation Editor of the Authoring tools in the AR module, the KBS module provides all related information for the objects.

Figure 5: Integrated IAR System

The integrated IAR system is depicted in Figure 5. The flow of the IAR system is as follows: First, the camera receives a real image from the aircraft, and then the AR module conducts the object recognition process in flow 1. Once the AR module recognizes the current object, the module sends recognized information to the UI/UX module. The UI/UX module receives information on recognized objects or events from the KBS in flow 3 when the user triggers an event by clicking the mouse or giving a voice command with the display of an augmented object in flow 2. In flow 3, the KBS module finds related information by using ontology-based repository and the KBS engine. All identified output of current information is displayed in Video view, IPC view, AMM view, Text view. The KBS module sends current information to a GUI.

Lastly, at flow 4, AR module receives the current information and displays the output of related data and menus to the corresponding location in AR view.

Context Management

To provide accurate contextual information in an effective manner, context management should be provided in the process of maintenance work (Wang, Boukamp, and Elghamrawy 2011). Context management allows technicians to approach a given maintenance task in an appropriate context.

The IAR system provides technicians with a context management function. Without it, technicians start a given task by reading printed maintenance documents and find core components for the task. With the IAR system, however, they can specify the context by clicking components in the ontology tree before recognizing specific parts based on the AR module. Therefore, there is a need to narrow down the scope of aircraft components for object recognition. For example, distinguishing the landing gear on the left-hand side from that on right-hand side is not an easy task if only vision technologies are used. It is much easier for the technician to specify contextual information by clicking the information in the ontological context.

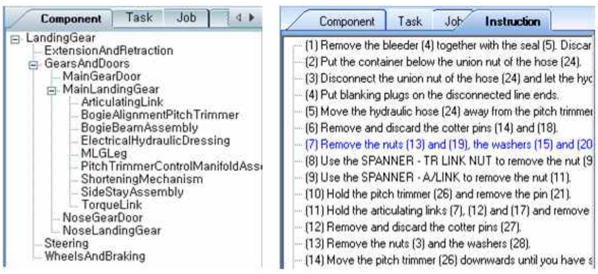

Figure 6: Macro and Micro Views for Context Management

Given that an aircraft has main components such as the main gear door and landing gear, the domain knowledge is reflected in ontology modeling. There are some tasks that can be applied for each component such as installation and removal. The landing gear consists of medium-sized parts such as articulating links and pitch trimmers. The KBS module allows technicians to choose specific components to narrow the context for a given task by using the menu tree view in the UI/UX module.

Figure 6 (left) shows a macro view that narrows the context. Once a technician chooses a task, the IAR system narrows the scope of object recognition, and the AR module starts to recognize objects within the given context. After the recognition of specific parts for a single task instruction, the IAR system maintains the context as the technician works through the specific instruction. Figure 6 (right) shows context management at the level of a single instruction. Context management at the instructional level includes updates on a specific number of technical drawings from different manuals with a corresponding number of different manuals and tools required for performing the instruction. The AR module provides technicians with a preview, indicating the next camera position by providing a scene for the next instruction. The KBS module manages the current context through the Component-Task-Subtask-Instruction pair. Here the component and task correspond with the macro view, whereas the subtask and instruction correspond with the micro view. Based on the information of Component-Task-Subtask-Instruction pair which can be constructed from the user's interaction with UI/UX, the KBS module can maintain current context during aircraft maintenance work.

Case Study of maintenance work for the removal and installation of pitch trimmers in landing gear

The aircraft maintenance process involves millions of components and maintenance instructions and thus requires technicians to follow rigorous procedures to prevent operational errors. In addition, maintenance time is a cost-sensitive issue for airlines. In this regard, the IAR system is proposed to overcome safety and cost-related issues by assisting aircraft technicians to handle complex tasks with an intuitive interface in their maintenance work. During the IAR project period from 2009 to 2011, many on-site tests were conducted at KAL hangars.

A maintenance task for the landing gear of Airbus's A330 was chosen for the final test. Some of the board members of KAL and Airbus and researchers from INHA and USC attended the demonstration of the IAR system. Two technicians performed the removal and installation of pitch trimmer by using the IAR system during a period of about three hours. The removal and installation task was composed mainly of 19 and 27 instructions, respectively. The IAR system was developed to build an authoring tool for aircraft maintenance problems by integrating KBS with AR. By using this authoring tool, the removal and installation tasks of pitch trimmers were successfully designed and implemented. In addition to the KBS of pitch trimmers, we have incrementally built the KBS by modeling knowledge about the other parts by acquiring knowledge from maintenance engineers and various manuals. As far as AR is concerned, to test and evaluate the AR system with the actual aircraft in the real environment would cost about 100K USD a day if the aircraft had to stay at the hangar only for AR testing. Even if we experimented with the AR system using only regular maintenance hours, this would still result in increased maintenance hours. It is one of the challenges that remain to be overcome before this emerging application can be deployed for operational use.

The feasibility of the unified framework of AR and KBS for aircraft maintenance was demonstrated. After this on-site demonstration, additional benchmarks for different components such as aircraft engines and fuel pumps under different scenarios were implemented.

Figure 7 shows some screen-shots of the IAR system during the demonstration. In some cases, it was difficult to put the camera angle to a certain part of the aircraft. For those cases, the IAR system presented an additional operational view as shown in Figure 7 (top). AR content is appeared in the operation view. Figure 7 (bottom) shows a general case in which the angle was good enough to position a camera into a component of the aircraft. Once the AR module recognized features, augment content appeared in a specific coordinate of the object image. Through this view, technicians could check the necessary task and the method for the given instruction.

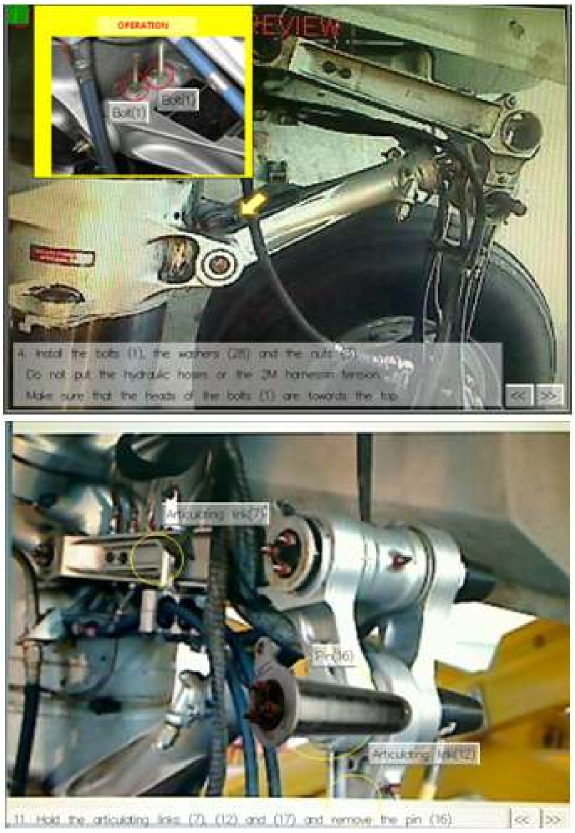

Figure 7: Screen shots of the AR view

Figure 8 (top) presents a real scene showing a technician following a given instruction. After the task and the method were determined, the technician moved to the appropriate location for relevant operations under the given instruction. Figure 8 (bottom) presents the AR view for the actual task and shows that the technician performed the sixth instruction in the subtask 32-11-15-420-052, a subtask of the pitch trimmer installation task. After the technician clicked on the components and pitch trimmer installation task, the KBS maintained the context and narrowed it to the instructional level. Figure 6 (left) shows the macro view such as the component level and the task level in the ontology-tree view in Figure 6 (left). After the macro view was given, the instructional level of context was updated automatically to support the technician.

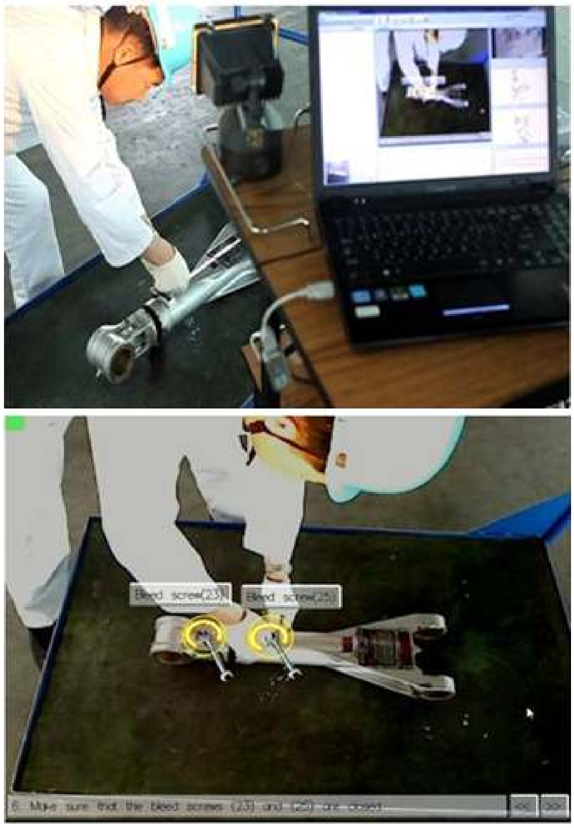

Figure 8: Actual Maintenance by the Technician

After the overall evaluation for pitch trimmer removal and installation tasks, maintenance engineers concluded that IAR system provided the following two types of benefits. First, the amount of preparatory work for the technician decreased by about 40 minutes. This reduction came from the following areas: printing the AMM, checking the availability of necessary equipment, referring to instructions and related information. These procedures required a close examination before the start of a given task by the maintenance engineer. Second, there was a decrease in the actual repair time. The technician finished a given task about 30 minutes faster by using the IAR system than by taking the manual approach. As the maintenance engineer navigated one instruction after another with the support of AR, different views from different manuals and different structural drawings were automatically provided and updated for the technician. Many different animated objects with context-aware services for each instruction were provided automatically as the maintenance engineer navigated one instruction after another. Finally, the IAR system was useful for the engineer as a simulator for aircraft maintenance work at the task level after the engineer completed basic training.

There are legal issues to be addressed in using the IAR system in practice. Maintenance engineers and inspectors are supposed to put their signatures on paper while working on tasks using paper-based manuals. If engineers use AR-based e-manuals and put their electronic signatures during removal and installation work using the new system, then the electronic process of maintenance work requires approval by numerous stakeholders, including government authorities responsible for aircraft safety.

Previous Research

Most studies of systems facilitating MRO process have focused mainly on AR techniques. (Crescenzio et al. 2011) proposed an application for aircraft maintenance and repair based on such techniques. They have used marker-less tracking techniques based on the SIFT or SURF for object recognition and tracking, and selected the oil-check task. However, no study has explored AR techniques integrated with knowledge-based systems for aircraft maintenance tasks, which is important in aircraft maintenance processes because manuals are regularly updated and many resources are used at many points.

(Zhu et al. 2012) proposed an authorable context-aware AR system to assist technicians with markers. They introduced context modeling, an essential step in developing context-aware services, and employed ontology-based techniques. Here maintenance technicians need to actively interact with and update maintenance knowledge. It is not possible to employ marker-based AR techniques in aircraft maintenance tasks because the attachment of physical markers to certain parts of an aircraft is in violation of various aviation safety and security regulations.

Discussion and Conclusions

This paper proposes the IAR system, which is based on a unified framework for AR and KBS to provide the specific context-based information to maintenance engineers. The specific context-based information is a UI/UX with the specific number associated in a structural drawing at an instructional level of the technical manual in another manual. In addition, the IAR system focuses on the technical development of AR tracking, annotation, and KBS components to support the efficient and effective performance of aircraft maintenance tasks. The IAR system involves vision-based tracking, annotation, and recognition methods needed to align annotations with camera images. The AR module enhances computer vision techniques for real-time and robust of object recognition and tracking in very challenging aircraft settings. The KBS module addresses methods to handle and manage the huge amount of data to support AR and consistent resource maintenance. Unlike other AR-based systems, the IAR system provides a unified resource framework with the context management perspectives. By unifying the AR and KBS techniques within a platform, aircraft maintenance engineers can conduct maintenance work in the following:

- Context-aware camera views through the integration of AR with KBS to obtain specific technical instructions on real-time basis
- Unified and summarized views for the integration of maintenance resources such as videos, photos, links, and figures, and other resources with manuals according to the current AR context

However, despite current performance of the IAR system, there remain some challenges. As in the case of all other object recognition techniques, strong light variations affect the object recognition performance of the system. On-site environments change frequently according to weather conditions and whether the hanger door is open. In this regard, future researches are needed in the following areas:

- Devise new methods that can enhance the robustness of object recognition that do not depend on changes in background scenes and illumination
- Examine the semantic web technology to support intelligent AR in the aircraft maintenance domain by accessing resources through wireless Internet based on smart/wearable devices
- Explore new functionalities of the authoring tool for many technicians to cooperate in multiple jobs, support many users to create AR content in a collaborative manner

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