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“A MOBILE SOLUTION TO ENHANCE THE TROUBLESHOOTING TECHNIQUES AND MAINTENANCE PROCEDURES OF THE ENGINE BLEED AIR SYSTEM ON THE BOEING 737 AIRCRAFT”

TESIS

PRESENTADA COMO REQUISITO PARCIAL PARA OBTENER EL GRADO ACADÉMICO DE:

MAESTRO EN CIENCIAS CON ESPECIALIDAD EN SISTEMAS DE MANUFACTURA

POR:

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Resumen

A lo largo de los años el mantenimiento y reparación en la industria aeronáutica han desarrollado diversos sistemas de entrenamiento y recuperación de información necesaria para asegurar eficacia en sus labores y seguridad para los pasajeros. Por el otro lado, las tecnologías de información han alcanzado un grado de madurez mayor y han surgido nuevas propuestas de mejora para la industria aeronáutica, se ha comprobado que la tecnología de realidad aumentada y realidad virtual impactan fuertemente de manera positiva el desempeño de las labores donde ensambles complejos están involucrados.

El presente proyecto de investigación propone el uso de hardware móvil como tabletas o teléfonos inteligentes como herramientas para el aceleramiento de la transferencia de conocimiento para las tareas de aislamiento de fallas y mantenimiento aeronáutico en ensambles complejos donde los procesos de reparación no son necesariamente lineales, se propone como caso de estudio el sistema neumático del avión BOEING 737 perteneciente a la compañía Aeromexico. Se desarrolla una aplicación de realidad mixta por un método iterativo, para fortalecer los manuales actuales de la compañía que permite el acceso rápido a cualquier estado de la reparación en tres toques en la pantalla del dispositivo, así como la comunicación vía correo electrónico y despliegue de múltiples ayudas como texto escrito, videos y modelos 3D. Por último se analizan los resultados obtenidos de la implementación y se discute el impacto de la propuesta en la industria aeronáutica.

Dedication

I would like to dedicate this work to my family who accompanied me in this journey and encouraged me to always give my best in every challenge.

To my best friend and the love of my life Dulce who gave me her unconditional support during this time.

Acknowledgments

I wish to thank my committee members who were more than generous with their expertise and precious time who provide me with exceptional guidance, knowledge and friendship. To Dr. Eduardo Mendívil who always encouraged me to think out of the box and believed in me by providing constant support in this journey, to Dr. Ciro Rodriguez who welcomed me in the master program and guided me in some many aspects of my formation and to Dr. Hector Siller who was always there to advise me and showed me that you are not too busy to tackle new challenges.

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I also would like to acknowledge the SEMARA team for this great experience as coworkers and dear friends in every challenge overcome (from coding/modeling problems to visa issues). Thank you Valencia group for its guidance on the project implementations. Thanks to Ricardo, Sujania, Alberto, Octavio, Alejandra and the crew for their patience, support and for so many discussions during this time.

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Nomenclature

AR: Augmented Reality

EBAS: Engine Bleed Air System

HSV: High Stage Valve

MRO: Maintenance, Repair and Overhauling

AMP: Aircraft maintenance personnel

PM: Preventive Maintenance

CM: Corrective Maintenance

OEM: Original Equipment Manufacturer

APP: application normally refer for mobile markets (android app / iOS app)

ICAO: Civil Aviation Organization

FAA: Federal Aviation Administration

EASA: European Aviation Safety Agency

USA: United States of America

Chapter 1 Introduction

Introduction and Justification

Advancement in technology and the commercial devices permit us to enhance sight through the interaction of virtual animations or content with the real world, they also allow touch sensing capabilities as a way of interaction with software, the Augmented Reality (AR) technology permit the study of many possibilities for innovative applications in an extensive variety of fields, as many as our own imagination permits. For the purpose of this work, AR along with mobile devices are tools considered for maintenance procedures and troubleshooting applications in the aeronautical industry. In this section an introduction is presented of the impact area of this investigation in the aeronautical engineering field.

The market for the maintenance, repair and overhauling (MRO) in aviation is very interesting in an economical perspective according to the Aeronautical Repair Station Association [1] the civil aviation MRO market generated $80B in economic activity in 2009, $39B where aported by USA, the opportunity for improvements in this market is latent to lower the actual costs of the MRO, this means that better service to costumer can be offer with excelent quality.

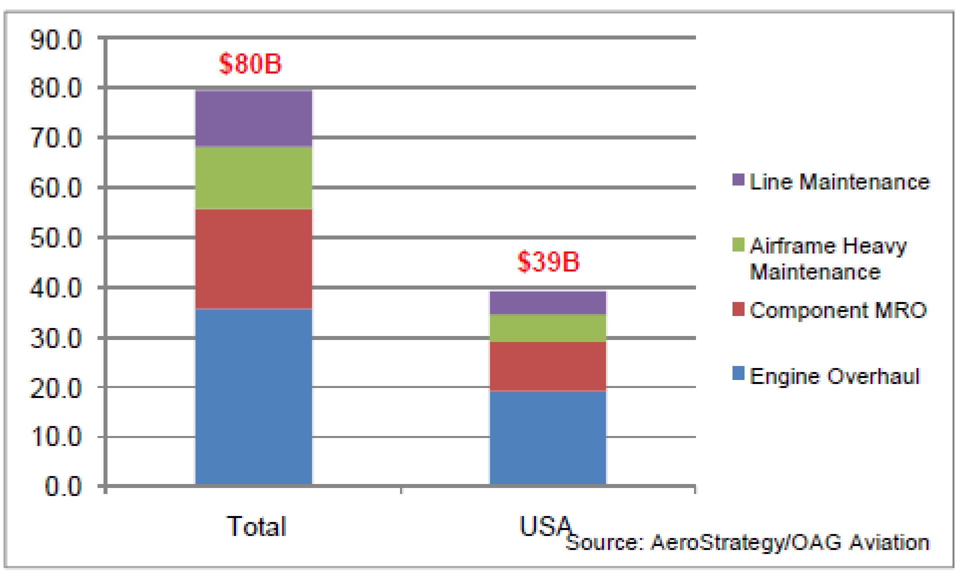


Figure 1 MRO market and USA participation [1]

In 2008 the world civil aviation fleet was 77,134 aircraft [1] where the 47% belong to North America, all of these airplanes are constantly going to different maintenance procedures that imply several cost for the users. The world aviation fleet takes maintenance procedures for the four different MRO market: airframe heavy maintenance, engine overhaul, component MRO and line maintenance.

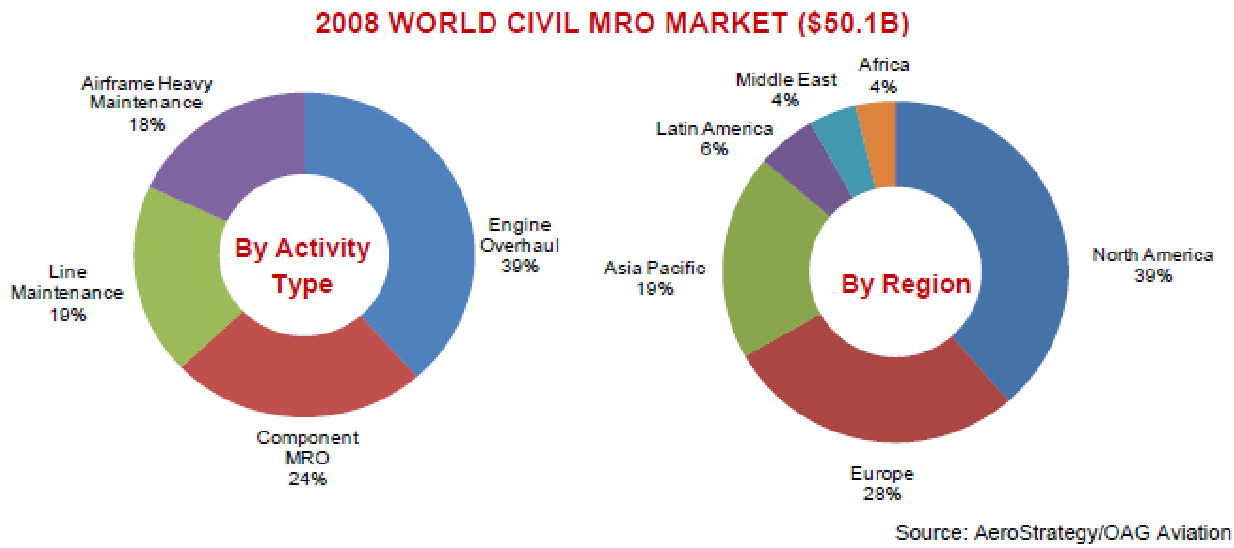


Figure 2 2008 World civil MRO market [1]

One of the major investments in labor is in the airframe heavy maintenance as shown in Figure 3, where a detail inspection is performed, the proper training of personnel will be translated in reducing time man-hours for maintenance and cost of retaining the aircraft in the hangar.

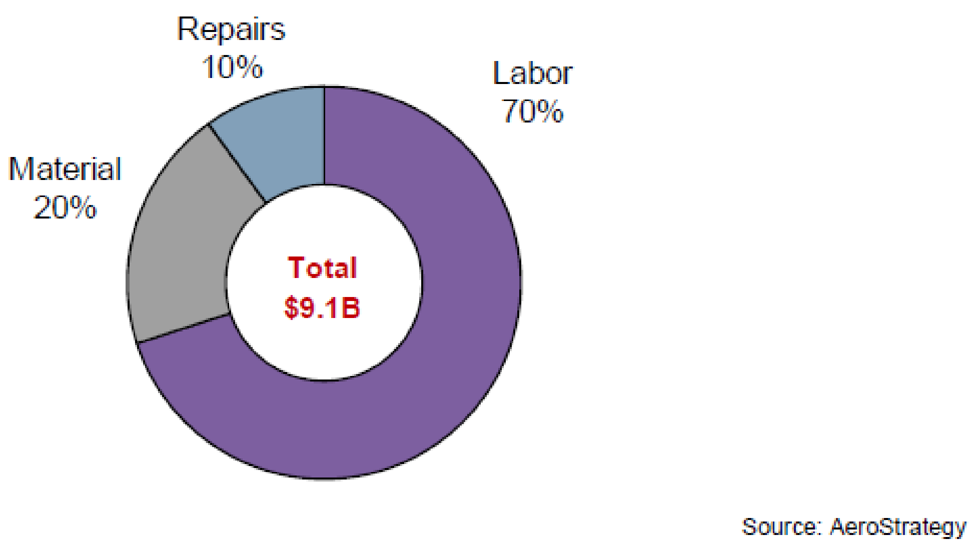


Figure 3 Airframe heavy maintenance cost structure

When the airline needs to provide line maintenance, the operators become a main asset in the organization, because 88% of the work is performed by them and only 12% is done by outsourcing [1], the previous knowledge of the systems and subsystems of the aircraft will impact in the efficiency of the service that is offered by the airline. In this kind of maintenance procedures, the transit, daily/weekly and “A” checks are done to ensure the security of the passengers. Every airline has developed a system to transfer the knowledge from the experienced operators to the new hired ones that must performed the checks with few contact with the physical systems of the aircraft.

The advancements of technology has permitted that the accidents due to the components of the aircraft is reducing every day buy the failures, that are caused due to human error, are increasing with the complexity of systems in the aircraft, at the beginning of aviation 80% of the faults and accidents were caused by the machine and nowadays the 80% of the accidents are due to human causes leaving only 20% to the machine failure [2].

Airline	Location	Year	Incident / Issue
Eatern airlines L-1011	Miami	1983	Incomplete installation led to engine problems
Japan airlines	Tokyo	1985	Incorrect installation led to the rear pressure failure
Aloha airlines 737	Hawaii	1985	Inspection failure led to fuselage failure
BM airtour 737	Manchester	1989	Engine inspection failure led to loss of system
United airlines DC10	Iowa	1989	Engine inspection failure to loss of system
British airways BAC-111	Hampshire	1990	Wrong bolts led to the cockpit window blowout
Continental express	Texas	1991	Tail failure as task not completed before flight
Nortwest airlines	Tokyo	1994	Incomplete assembly led to engine separation
ValueJet	Florida	1996	Fire in hold due to incendiary cargo
Air mid-west beech 1900D	North Carolina	2003	Incorrect rigging led to elevator system control failure

Table 1 Maintenance related incidents

History has shown (Table 1 [3]) that there is a lot work to do in the methods for training and transfer knowledge to new and experienced operators, according to the a survey of the Australian Transport Bureau [4] about the occurrence of accidents during maintenance procedures, the most common outcomes were systems operated unsafely during maintenance, towing event and incomplete installation.

Another study by Boeing and the U.S Air Transport Association member found was one of the factor that contributed to accident where five or more people were killed, 39 of the 264 (15%) from 1982 through 1991. From these 39 accidents they can be divided by its cause [3]:

- 23% involved an incorrect removal/installation of the components
- 28% involved a manufacturer or vendor maintenance/inspection error
- 49% involved an error due to an airline´s maintenance/inspection policy
- 49% involved poor design which contributed to the maintenance error

This situation can be reduce by the use of an innovative method that new technologies are offering to us in this days, the hardware required to move digital information is getting smaller and more efficient also the new visual technologies can be used for the purpose of training in the aviation industry.

Augmented Reality (AR) is a variation of Virtual Environments (VE), or Virtual Reality as it is more commonly called. VE technologies completely immerse a user inside a synthetic environment. While immersed, the user cannot see the real world around him. In contrast, AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world. Therefore, AR supplements reality, rather than completely replacing it [5].

Furthermore AR technology is particularly suited for maintenance industry, as it can be easily implemented in several processes. AR can enhance the user's view of the surrounding scene with different content that include visual animations, sounds, written instructions or static images. Using AR can potentially reduce the numbers of errors during maintenance tasks; in fact AR provides information that is generally not easily available or whose retrieval is relatively demanding. In general many processes in manufacturing, aviation and automobile industry deal with assembly tasks. During maintenance operations, mechanics have to deal with a large amount of different parts that represents a large proportion of search time: standard manuals or handbooks can lead inexperienced operators to frustration and poor performance. As shown in Table 2 the major unsafe acts that lead to accidents are related to memory lapse (21%), procedures shortcuts (16%) and knowledge-based error (11%) this can be avoided by having the right information at right time, if the operator does not remember something he can consult his mobile device to access the manual, also the procedures shortcuts and knowledge-base error can be minimized or eliminated by educating the operators in the proper procedures of repairing the aircraft.

	Airline	Non-airline
Memory lapse	21%	20%
Procedure shortcut	16%	21%
Knowledge-based error	11%	18%
Trip of fumble	9%	11%
Failure to check	6%	2%
Unintended action	3%	6%
Failure to see	5%	6%

Table 2 Unsafe acts in occurrences [4]

Current training model of the Aircraft Maintenance Personnel

The aeronautical industry personnel can have varying degrees of educational background, from self-taught individuals to holders of university degree, but independently of their background every person must take a very comprehensive technical training that provides the necessary knowledge, skills and attitudes for assuming responsibility over the health of the components and system of the aircraft. The International Civil Aviation Organization describe that a license is the means by which a state authorizes a license holder to perform specific activities which unless performed properly, could jeopardize the safety of aviation [3].

Theoretical and practical training must be given in order to have an operator with valid license; this training is according to the content and required standards by international association such as Civil Aviation Organization (ICAO), Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA).

The different stages of the basic training course are the knowledge training, knowledge examination, practical training and practical assessment, at the end the student must be competent at using tools and equipment and working in accordance with maintenance manuals. In the first stage the individuals take classes and receive only theoretical information, later they must connect this knowledge in the practical assessment and at the same time develop the necessary skills to succeed in the examination a later ensure the health of the aircraft and the security of the passengers. The profession of aircraft maintenance requires continual education.

In fact, regardless of the task, aircraft technicians must always refer to the maintenance manual for the specific aircraft to obtain proper procedures and specifications. A great amount of time is spent searching for instructions, which increases maintenance time, worker stress, and decreases overall job performance [6]. If the task implies several procedures for example troubleshooting the engines this task will call different procedures of removal and installation of components. Neumann and Majoros identified that **45%** of a AMTs shift is spent finding and reading instructional procedures for job tasks [7].

In order to become a certified aircraft maintenance personnel one operator must complete the basic training, on the job training, and type/task training, but as reviewed in this document currently the principal causes of failure in many accidents in the aviation industry are lack of technical training and skills.

This research is focusing in the basic training and on the job training where the operator have to familiarized with the technical data of the manuals and the physical components of the systems, taking into account all the details (torque of certain parts, warnings, checks, etc.) and regulations that must be followed to release the airplane, also the operator have to develop a mind map of the correct functioning of the system and he must be able to troubleshoot if necessary. In the next section the proposed model of training for this stage will be revised and compared to the current training model.

Proposed model for training and enhancing knowledge of Aircraft Maintenance Personnel

The aeronautical organizations had made great efforts in standardizing and training for maintenance area to ensure quality in the different aspects of the services that they provide, but there is still a lot work to do for minimizing the accidents and take the proper care of the aircraft. The need for new tools that can make the process of training more efficient is arising and not only for training also for the use in the different maintenance task in practice. Carrying on big quantities of printed manuals is not the best way to learn and have a clear concept of the functioning of the machine, as show in Figure 4, when a fault of a system has arisen the manuals try to lead the operator through all the steps and checks to isolate the faulty component and give the proper maintenance, this steps implies going back and forth through different stages of the checks and different manuals, for example to check the bleed system, the operator must follow first the safety procedures to ensure the motor has no pneumatic power, this is the first package of paper, then he will start all the steps in the health check and corresponding 2D figures in different pages, this going back and forth through the manuals has become an issue, it is difficult to create the general map of isolation of faults and new operators tend to mechanize their labor instead of leaning and mastering the process.

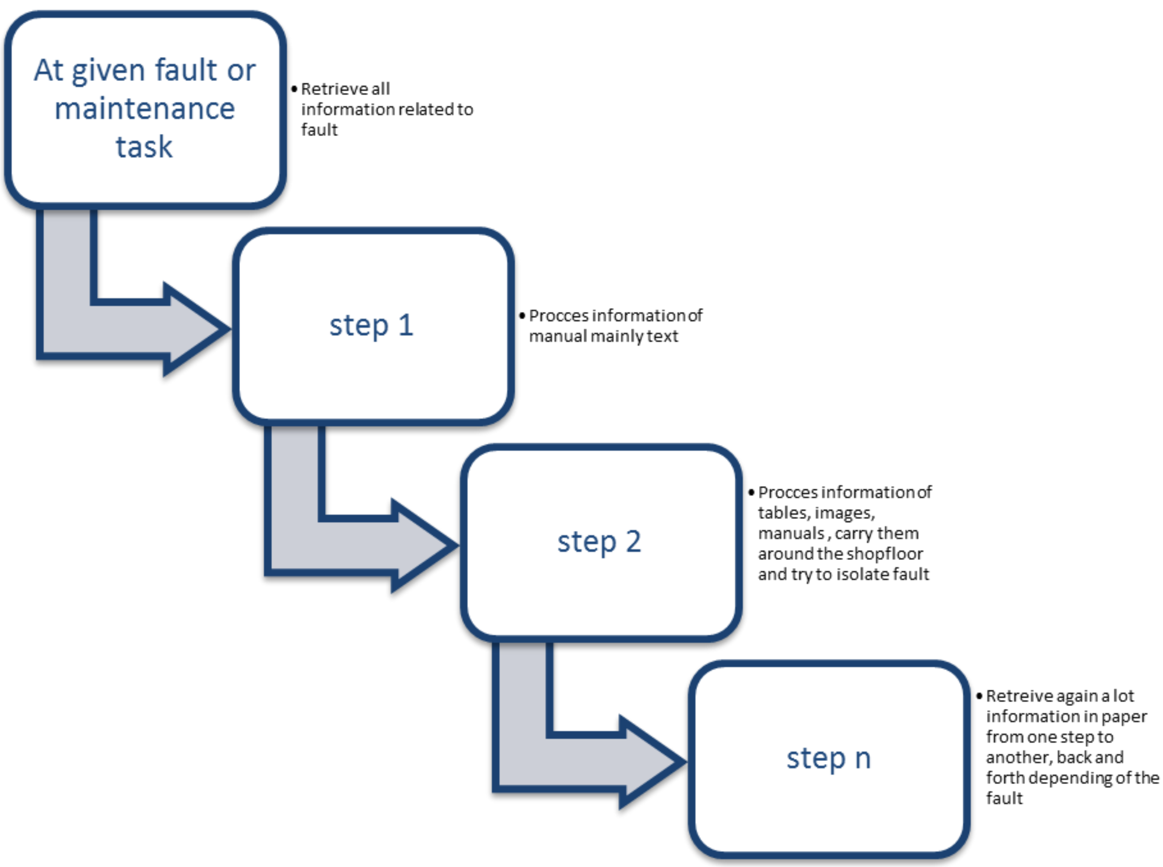


Figure 4 Current process of troubleshooting and maintenance with printed manuals

The purpose of this work is to propose an innovative tool than can potentially improve the cognitive process of training and troubleshooting techniques of the aircraft, but also can be used to the everyday task by capturing the know-how and helpful tips of more experienced operators, as shown in Figure 5 this tool will present the knowledge as a portable asset, giving all the information needed by only one touch apart from each other, the operator will be able to form a clear concept of the task and he will access the information at right time like tables of normal functioning of the systems, written instructions of different manuals, images and virtual content to guide the task. This tool is not intended to suppress the process of certification of operators by the different entities in the aviation industry on the contrary is a proposal for enhance the current process training and practical procedures at the hangar and this way reduce the accidents and efficiently take care of the aircraft troubleshooting and maintenance procedures.

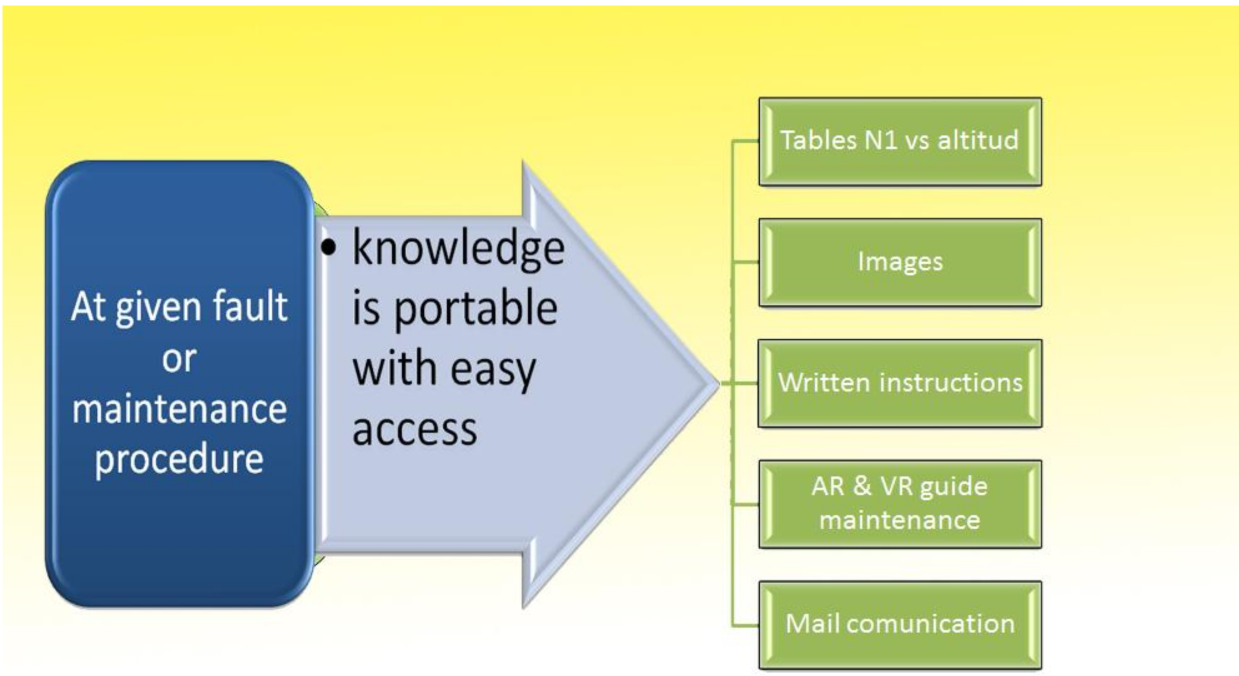


Figure 5 Proposed solution to accelerate transfer of knowledge and troubleshooting techniques with all information in line system installed on mobile device

Objectives

The motivation of this research is to improve the method of training of an aeronautical maintenance process with more information that is not available in regular work environments, in this way accelerate the cognitive process that new users have during training and the stage of familiarizing with complex machines.

The scope of this project is to create a prototype system by means of mixed reality (augmented reality / virtual reality) [8] and gestural interface to enhance the cognitive process and ability of a user that holds a job in complex assembly processes that are commonly found in the aeronautical area. This tool is going to be developed for mobile devices with touch screen that have iOS or Android operating system. Is worth to mention that the augmented reality system is scale and pose invariant, this enables the user to move and locate the tablet in the best position for accessing the graphical information.

During the investigation is expected to accelerate the transfer of knowledge from the current manuals of maintenance and troubleshooting procedures of a company by using the augmented reality technology along with the several advantages that mobile device have, like portability, low cost, friendly interaction and savings in printed manuals.

The case of study on this project is the troubleshooting techniques and maintenance procedures of the engine air bleed system of the BOEING 737 aircraft that has two CFM56-7B engines, where according to the company, the system is one of the most prone to failure or frequently recurring in repairs, thus requiring the most attention and thorough maintenance scheduled tasks.

During the development of this project the questions that we are looking to respond are: Is this new tool going to improve the quality of training and troubleshooting the engine? The hardware is reliable enough to maintain the information with easy access at any moment? And from the perspective of the users, are they going to be willing to use the system?

Chapter 2 Literature review

Introduction

There have been several efforts to implement the augmented reality technology into the industrial world, but it is barely reaching the technology matureness to offer commercial applications that have enough stability and ease of use, for example the case of black and white markers, yet there is new products that are been developed to strengthen the offer of new tools like markerless (texturized sheets), infrared tracking, geo-tracking , magnetic tracking or 3D object tracking that can be used with the rendering of virtual models. In the other hand new hardware is been fabricated every year with more capacities that can support complex algorithms and parallelization of tasks with low weight to enhance ergonomic capacities.

According to Milgram the reality - virtuality continuum is defined in Figure 6, where the cases of augmented reality (AR), virtual reality (VR) and mixed reality (MR) can be clearly identify with their respective end point at the real environment or the pure virtual environment, this project will be centered in the continuum because it is constrained for two environments: training and in situ troubleshooting (developed of the project showed with the blue point Figure 6).

For controlled environment in the classroom is very likely that the user can print the marker to track the models or use the prototype turbine made to scale, where the augmented reality system can be advantageous, but there is situation in situ where the operator most repair the engine, he will be able to take the tablet and follow the instructions in a virtual mode en case he cannot reach a the marker independently of the virtual o augmented reality mode of the system, the operator will be able to interact with the application with touch/gestural screen provided by the device.

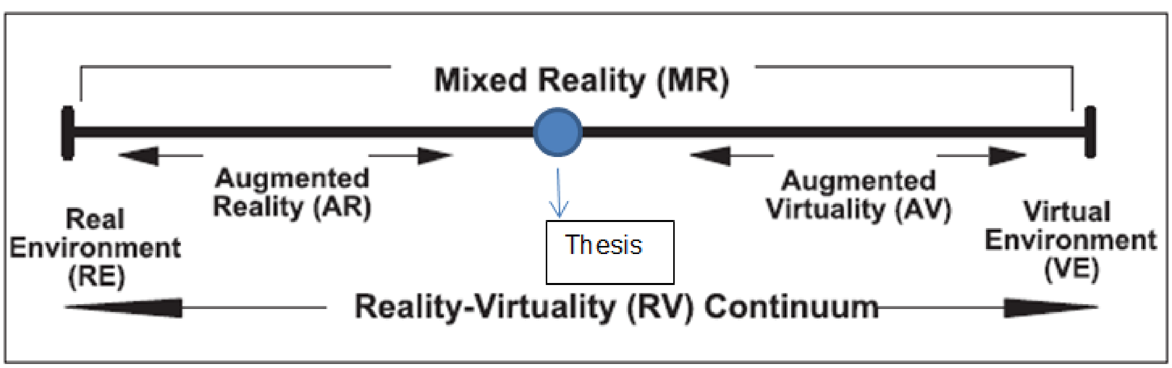


Figure 6 Definition of Mixed Reality [8]

Augmented Reality development for the industry

The research community and the industry have made several associations to push further the development and implementation of the augmented reality technology along with hardware that is custom fabricated or acquired from the market, the goals vary from group to group depending of their interest, in the next section an investigation of the relevant projects and research related to this investigation is presented (see Figure 7).

One of the representative examples of the creation of a consortium between various industries is the ARVIKA project that tested augmented reality in the development, production and service in the field or the service of the machines and systems that are required for production for the automotive and aircraft industries this is an effort to unified the development of European AR projects [9] (see http://www.arvika.de/www/e/topic2/presse.php to review projects from ARVIKA).

In automotive industry there is a wide range of implementations for example, Platonov et-al developed a prototypical AR system for maintenance of BMW 7 Series engine which utilized a monocular camera setup as well as a light weight mobile hardware platform for visualization, the main problems in this was the error accumulation during the tracking and lighting changes [10]. Henderson and Feiner created a prototype for conducting routine maintenance task inside a armored vehicle turret, they used a tracked head worn display (by infrared sensors) to augment a mechanic´s natural view with text, labels, arrows and animated 3D models, reduced time in the performed task and less overall head movement was reported (up to 47% against LCD screen and 56% against Head up display), the qualitative test for the mechanics showed that the augmented reality technology was intuitive and satisfying [11]. Chen et-al built a design evaluation environment that combines a full-scale car display and a visual evaluation system, the image of a car was transmitted via wireless communication onto a personal digital assistant. Then when the image of the car was updated it was constructed on the fly on a PC server and send back to the head mounted display and the personal digital assistant (PDA); multiple users could visualize the car simultaneously and discuss to enable the evaluation of the design [12].

The aeronautical industry can be helped with AR and mobile technology, the need for tools that can increase quality to ensure safety of passenger and longer life to the components of the aircraft is vital for the market, Henderson and Feiner also worked with what they called opportunistic controls that are a class of user interaction techniques for take advantages of unused affordances already present in the domain environment, this allowed the use to have a gesturing interface with the real work besides the augmented reality with black and white markers, for example they could touch a bolt in the rolls Royce Dart 510 turboprop engine, this action would activate a trigger for the action programmed like deploying more information, sound or finished the task [13]. Macchiarella and Vicenzi worked with the inspection of a power-driven rotary oil pump from a model T53-L-13B turbine aircraft engine, the main purpose of the investigation was to recall the names of the major components and several selected functionalities for the components to measure the immediate and long term memory recall with different technologies like AR, Interactive AR and print text, the equipment used for this experiment in the AR part was a desktop CPU and Toshiba screen. The principal finding was that AR did not enable learners to recall more information during testing, but it did apparently enable them to recall a greater percentage of what they had learned. Further investigation was necessary to conclude [14]. De Crescenzio et-al investigated daily inspections of the Cessna C.172P and airplane that flight schools often use, they focused in the maintenance check performed before the first flight of the day by using markerless camera pose estimation that tracked the natural features in the physical objects. In this study the participants seemed to understand how to use it, their level of satisfaction was 8/10 and they were willing to use it in everyday assignments [15].

In the side of manufacturing and industrial engineering, Reinhart and Patron developed a modular AR system for guiding manual assembly and for use in assembly planning, they integrated a database to quickly expand to different processes where the 3D model where inserted to the database [16]. Zhang et-al integrated the AR technology with a 3 axis CNC machining environment. Render of cutting simulation between a real cutter and a virtual environment was done. Their experiment showed that in situ simulation system can enhance the operator´s understanding and inspection of the machining process as the simulation are performed on real machines for purposes of training and dry runs in the machine [17]. Lee et-al proposed a method of constructing a mixed reality based digital manufacturing environment where real objects, such as real images, are combined with the virtual space of virtual objects. This project was created for the virtual layout planning with the use of image-based tracking method which found and arbitrary feature from actual images, such a safety sign, such images replace the artificial squares markers [18].

The medical industry must be considered because there is procedures that can be enhanced with the use of this technology also there is a big market for the improvement in this field, for example Nicolau et-al presented an augmented reality guidance system for liver thermal ablation an interventional radiology the system could take into account changes in position due to respiration. Besides performing lab testing they also experimented with eight patients with tumors. The system accuracy was reported to be 4.5 mm, what fits medical requirements later they were to investigate the use of electromagnetic tracker to compensate needle bending [19].

Weiss et-al proposed an AR system for Magnetic Resonance Imaging (MRI) guided needle placement in a spine phantom, they validated needle position with an electromagnetic tracking system to provide tip position and orientation, in this study 57 of 60 needles were positions successfully with good results in the measurements of error [20].

Other big interest for the application of the AR technology is marketing and tourism, these industries are taking advantage of AR since the early stages of development, for example Chubassi presented an augmented reality tourist guide on mobile devices by using the different capacities of new mobile technology like cameras, location, orientation and motion sensors. The augmented information was obtained by matching a camera image to images in a database that have geotabs [21].

In Figure 7 a summary of the different research projects related to the industry is shown where the application area and principal achievements are described.

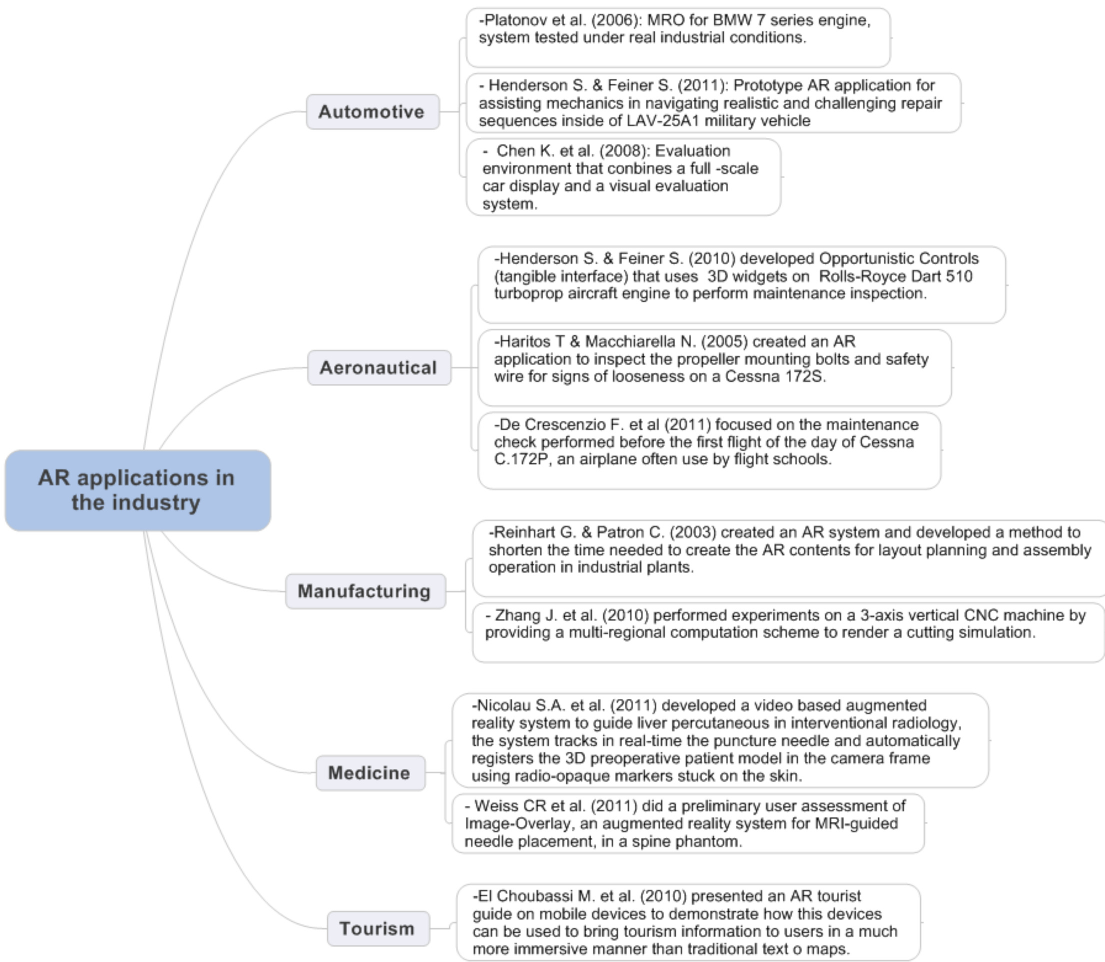


Figure 7 Application of AR in the industry related to the work presented in this thesis

Troubleshooting software implementations

As technology advances and manufacturing capabilities improve there has been an increment on the need for specialized software to troubleshoot the complex systems that are fabricated because basically, all non-trivial troubleshooting domains are NP-hard [22]. The software must manage a lot of information to simplify it for the technicians or final users and it should be designed ergonomically to ensure that the tool will be used and will not interfere with the task.

For example in 2009 Castellani et-al conducted an study to examine the properties of different assemblies of people, resources, technologies and spaces to inspire design for the different troubleshooting situations, they covered different dislocations between various aspects of the study in the two cases of troubleshooting self-conducted and expert-supported, the dislocations considered in the prototype were **physical** between the site of the problem and site of problem solution, **conceptual** between the users and the expert and the **logical dislocations** between the support resources and the status of the ailing device itself, this study developed a set of integrated mechanisms and systems aimed at harmonizing the various elements and at capturing, where possible, the haecceities of the device [23]. The dislocations were covered by integrating troubleshooting software in the copy-machine and a call center of experts that could be consulted.

There are systems for web technology like what Liang proposed, the author made a troubleshooting task model of automobile chassis by using web-based system that guide the users with virtual animations and written instructions this prototype environment for distance learning. This tool was looking to eliminate the limitation of space and time. The tool was not designed for a specific model of automobile and the system run in a desktop computer with internet access [24]. Johnson et-al created a system for developing virtual environments in which pedagogical capabilities are incorporated into autonomous agents that interact with trainees, the agent could monitor progress and guide the persons through different activities like operating a High Pressure Air Compressor (HPAC) of a naval turbine; the environment was constrained to the virtual reality in the computer and the interaction from the users to the system was through buttons in the screen [25].

Ong et-al presented a practical framework in which a system to monitor and maintain turbines was introduced in the emerging grid computing paradigm that can provide the necessary resources to develop the system called Distributed Aircraft Maintenance Environment (DAME, see Figure 8), abnormal behavior could be isolated by using Case-Based reasoning (CBR) which is a problem-solving paradigm that resolves new problems by adapting the solutions used to solve problems of a similar nature in the past also it was incorporated model-based fault detection and isolation (FDI) to estimate and analyze responses of the turbine [26]. This tool was only oriented to analyst and expert engineers working together to gather data to perform maintenance and fault diagnosis of aero-engines there were no training capabilities in the system.

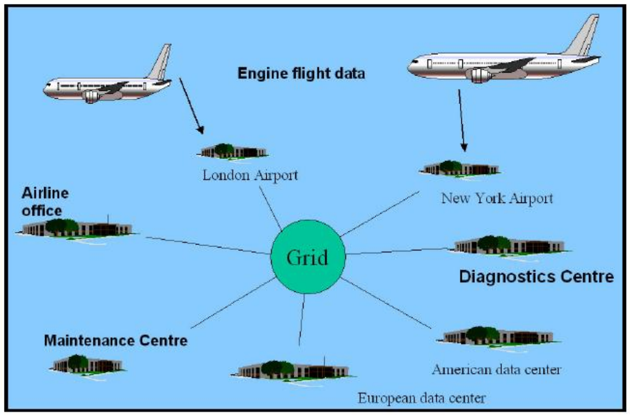


Figure 8 Distribution of data in a virtual engine maintenance environment to find abnormal behavior in turbines [26].

In the side of the supply chain Haider et-al developed a concept demonstration called the Automated Test Equipment Multi-Agent System (ATEMAS) to achieved a mechanism for effective and efficient reliability and maintainability predictions for avionics components that can work together with the Maintenance Management Information Systems to calculate the likely obsolescence of avionics parts to enable operator to deal with obsolescence proactively instead of only react to obsolescence in components [27].

Dugri investigated Decision Analysis and Bayesian Networks for generating an optimal decision sequence for troubleshooting; the model was applied to the **Engine Air Bleed System of the Boeing 737** the objective was that operators adopted the model as part of their effective troubleshooting procedures but the investigation conclude that it is impractical to apply in complex real world scenarios due to the complexity of the problem and the generation of the solution [28].

In the following table eight different works are presented, each publication is related with the present investigation by using mixed reality technology for troubleshooting complex mechanical systems, the table also shows how this project differentiates from the work in the literature. There is few applications of mixed reality in the troubleshooting domain, only 9 published works were found in Scopus database [29], the main differences between those and the troubleshooting / mixed reality implementation for the EBAS are marked.

Contribution					
Author Year	Application	Modeling & Texturizing	Tablet (Android & iOS)	Communication	Gesturing interface
Mixed reality system to enhance troubleshooting and procedural task. Mail communication is allowed. Developed for tablets with Android or iOS operating system.					
Rios et al. 2012	Aeronautical BOEING 737	x	x	x	x
Mixed Reality (MR) system; It shows how remotely situated people can collaborate around physical objects which are not mutually shared, without introducing new interactional problems, such a representation can create reciprocal viewpoints. Identified physical, conceptual and logical dislocations					
-O'Neill, J et-al. -Roulland et all. -Castellani et al. 2011	XEROX Copy machines. The mixed reality was for the expert far away from the machine	x		x	
Mixed Reality system that **can be** applied to interactive visualization scenarios in diverse human-assisted operations; By means of Tangible Interfaces gesturing recognition, it is possible to activate menus, browse and choose menu items or pick, move, rotate and scale 3D virtual objects					
Dias et al. 2003	Analysis of possible applications	x			x
TeleAdvisor is a novel solution designed to support remote assistance tasks in many real-world scenarios. It consists of a video camera and a small projector mounted at the end of a tele-operated robotic arm.					
Gurevich et al. 2012	Not specific (TV case) hands free, mounted on wrist			x	x
The “Sandra” project aims at even further refine – and to introduce a state of the art – fault isolation maintenance concept for the Saab JAS39 Gripen aircraft. Based on an easy-to-use PC based graphical tool, Fault Isolation on dedicated aircraft monitoring and safety check result data is specified.					
Petersson & Fransson 2007	Aeronautical Saab JAS39 aircraft			x	x
Troubleshooting task model of automobile chassis by using web-based system that guide the users with virtual animations and written instructions this prototype environment for distance learning.					

Liang 2008	Automobile chassis	x			
Developed a game engine to have a virtual operation system future applications could be the guide of user through routine troubleshooting. In addition to the proven applicability for training personnel. Development initiative between Chevron Corporation and SAIC					
Stadfford & Hauser 2010	Simulation/modeling in the oil field environment	x		x	
Virtual reality and Augmented Reality software. Automatic path planning and collision avoidance					
Haist 2008	Set up and manage a remote maintenance operation for a thermonuclear fusion reactor	x		x	

Figure 9 Comparison of different Troubleshooting and Mixed Reality implementations with the work presented in this thesis

Summary

In this chapter the state of the art of the AR technologies and different implementations of information technologies have been reviewed. As showed before there are different trends of the industrial applications of the software technologies for industrial processes where mechanical components are involved but there are few projects that are actively using AR in mobile devices for training and in situ assignments with the capability of interaction real-virtual environment, even though the research community is starting to see the opportunity in for AR for small and ergonomic hardware to enhance industrial processes.

The following section presents a review of the generalized state of the art of the publication related to this investigation, Scopus database was used to perform the queries [29]. In the last years the number of publications on this subject has significantly increase for example, Table 3 presents the total number of articles in conferences and journal related to the development of the augmented reality technology, where the reader can identify that the development for mobile hardware is still in an early stage of development when compare to the work done in tracking techniques.

Category	TOTAL	%
Augmented Reality or Mixed Reality	6655	100.00%
Interaction	1903	28.60%
Tracking	1326	19.92%
Mobile	1300	19.53%
Mobile devices (Tablet, PDA or handheld)	564	8.47%
Calibration	302	4.54%
Rendering	402	6.04%
Authoring	116	1.74%
Related to aviation	84	1.26%
Related to maintenance / assembly / procedural task	281	4.22%
Related to maintenance on mobile devices tablets	15	0.23%
Mixed reality system for troubleshooting and maintenance	8	0.12%

Table 3 Published articles (journals & conferences) from 2000 to 2012

Note: Data gathered from Scopus database: (TITLE-ABS-KEY("augmented reality" OR "mixed reality")) AND (TITLE-ABS-KEY("tracking") AND PUBYEAR > 1999

"Scopus developers claim to index over 14,000 STM and social science titles from 4000 publishers, stating that it is the "largest single abstract and indexing database ever built". The database claims 4600 health science titles are indexed including 100% MEDLINE coverage, 100% of EMBASE coverage and 100% of Compendex coverage (Compendex is the most comprehensive search database for engineering R&D). It contains 27 million abstracts with citations back to 1966. In addition to American journals, it includes European and Asia Pacific literature in both English and non-English. Indexing includes CAS registry numbers, MeSH terms, EMTREE terms and supplemental key terms added by indexers…" [30].

Table 3 shows that the work done in AR in the aviation industry is barely 84 articles published where main institutions that provided that publications are the Embry Riddle University, Boeing corporation and NASA, more affiliations are showed in Figure 10 [29].

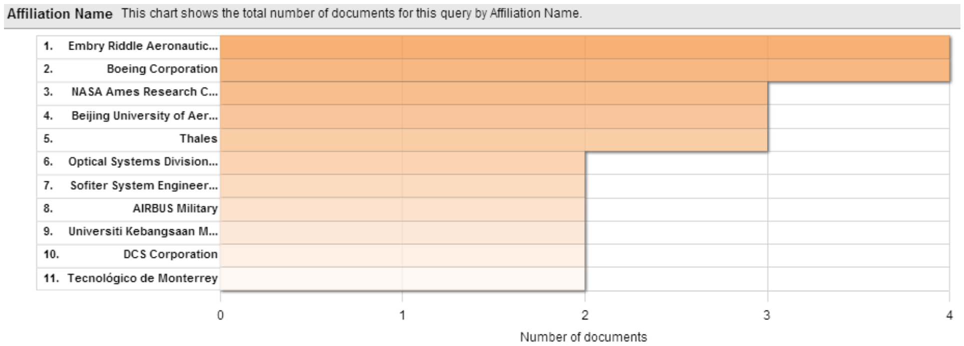


Figure 10 Affiliations with more publications of application of the AR technology in the aviation industry

The authors Ong and Nee from the National University of Singapore are the principal authors that have presented to the scientific community studies related to procedural knowledge or maintenance procedures using augmented reality [29].

Figure 11 Authors with more publications for AR in the maintenance / assembly domain

Table 4 shows the principal studies and measurements of the efficiency of the AR technology when used in the maintenance and assembly domain since 2000, in general the first published articles were when AR was compared with traditional written instruction and multimedia guides, then more complex comparisons came, between different presentations of AR for example with head mounted displays, with desktop monitors and different interactions methods (virtual button, gesture buttons, sensors).

TITLE			
Title Author Country, Year	Description AR system	Comparison system	Conclusions
Augmented reality in the psychomotor phase of a procedural task			
Henderson & Feiner USA, 2011	Augmented reality (AR) user interface designed to assist users in the psychomotor phase of procedural tasks	3D-graphics-based assistance presented on a stationary LCD	Participants overwhelmingly preferred the AR condition, and ranked it as more intuitive than the LCD condition
Exploring the benefits of augmented reality documentation for maintenance and repair			
Henderson & Feiner USA, 2011	AR tracked headworn display to augment a mechanic's natural view with text, labels, arrows, and animated sequences designed to facilitate task comprehension, localization, and execution.	Fixed flat panel display representing an improved version of the laptop-based documentation currently employed in practice AND AR providing untracked text and graphics and a fixed flat panel display	The augmented reality condition allowed mechanics to locate tasks more quickly than when using either baseline, and in some instances, resulted in less overall head movement
Opportunistic tangible user interfaces for augmented reality			
Henderson & Feiner USA, 2010	Participants performed a simulated maintenance inspection of an aircraft engine using a set of virtual buttons implemented both as Opportunistic Controls with AR	AR with virtual button only using simpler passive haptics	Opportunistic Controls allowed participants to complete their tasks significantly faster and were preferred over the baseline technique.
Assessment of communicative learning via Augmented Reality versus traditional method for aeronautical transportation			
Warden et al Mexico, 2011	AR method procedural task for maintenance	Traditional method with written instruction	Small sample cases at aeronautical sector
Augmented Reality efficiency in manufacturing industry: A case study			
Sääski et al. Finland, 2008	AR instructions that were projected on one lens of a head mounted display	Paper instructions	Usability and method evaluation

Augmented reality for assembly guidance using a virtual interactive tool			
Yuang & Ong & Nee Singapore,2008	Virtual interaction panel (VirIP), is a tool that can be used to interactively control AR systems. Interaction pen during the assembly process It is tracked using a restricted coulomb energy (RCE) network	AR visual assembly tree structure (VATS) is used for information management and assembly instructions retrieval	The results show that the AR-based method can provide an efficient way for assembly guidance.
Augmented assembly using a mobile phone			
Hakkarainen et al. Filand, 2008	Mobile phone based augmented reality (AR) assembly sy stem that enable users to view complex models on their mobile phones	N/A	People felt the interface was intuitive and very helpful in supporting the assembly task
Comparative effectiveness of augmented reality in object assembly			
Tang et al. USA, 2003	AR instructions in an assembly task	**Three instructional media** were compared with the AR system: a printed manual, computer assisted instruction (CAI) using a monitor-based display, and CAI utilizing a head-mounted display.	Reduced the error rate for an assembly task by 82% Measurement of mental effort indicated decreased mental effort in the AR condition
Augmented Reality (AR) for Assembly Processes Design and Experimental Evaluation			
Wiedenmaier et al. Germany, 2003	Tasks with different degrees of difficulty were selected from an authentic assembly process. AR system	2 other kinds of assembly support media (a paper manual and a tutorial by an expert)	AR support proved to be more suitable for difficult tasks than the paper manual, whereas for easier tasks the use of a paper manual did not differ significantly from AR support. Tasks done under the guidance of an expert were completed most rapidly.
Augmented reality in a learning paradigm for flight and aerospace maintenance training			

Macchiarella et al. USA 2004	AR system	N/A	Aerospace maintenance workers and pilots. Determined that AR-based learning effects long term memory by reducing the amount of information forgotten after a seven-day intervening time between an immediate-recall test and long-term-retention-recall test.
A mobile solution to enhance the troubleshooting techniques and maintenance procedures of the engine bleed air system on the BOEING 737 aircraft			
Rios et al. Mexico, 2012	AR system for symmetric assemblies	Written instructions	Quality increase in 24% and time of assembly reduce by 17.22% when using AR system with 2 mirror symmetries in the assembly
AR expert system of knowledge transfer for complex assemblies: application to aeronautical processes			
Alcazar et al. Mexico, 2010	AR system for assembly of model airplane motors (complex assembly)	Written instruction	25% less time for total assembly of motor with AR
Usability evaluation of different AR technologies for aeronautical maintenance			
Lerma et al. Mexico, 2012	AR with mark	AR markerless technology	Study showed that AR with regular black and white marker was better for industrial context but the markerless technology was more satisfactory to the user

Table 4 Principal studies of the improvements of AR technology when compared to others in the maintenance & assembly domain

From Table 4 it can be concluded that the replacement of written instructions by AR procedures will improve the quality of the output in complex assembly, and study to corroborated this results was made for assemblies with two mirror symmetries where similar results were found this study also contributes to the state of the art due to the differences in the assembly from other studies, specific details of this experiment will be given in chapter 5.

Title	Area	Contributions	Level of sophistication
Ababsa et al France 2012	Geological applications	Mobile augmented reality system dedicated to outdoor applications	Camera, GPS and inertial sensor

Emerenciano et al. Brazil, 2012	Network protocols	Collaborative Augmented Reality	Proposes a protocol for the transmission of visual cues. The protocol focuses on a client-server communication, where the client has the role to remotely supervise the activities, possibly sending interest points or instruction to the server
Lee et al. South Korea, 2012	Maintenance engineering	Knowledge Based System	suggests more improved smart maintenance system which can support engineering-knowledge to field engineers immediately as well as 3D CAD design information in working process
Neubert et al USA, Norway & UK, 2012	Maintenance engineering	AR application to guide a user through a machine tool setup and a printer maintenance task	Method for rapidly generating crude, appearance-based edge models consisting of a set of planes
Morkos et al USA, 2012	Automotive	Mobile configuration and augmented reality (wearable mobile devices) in a production environment	This paper details BMW's preliminary investigation and applicability study of implementing mobile devices within their manufacturing environment
Chang, J.-R Taiwan, 2011	Road management system	Mobile road management system (RMS) on under the Android platform e	Road engineers are able to download the mobile RMS for free, for anytime and anywhere monitoring and reporting of in-situ defects in road systems
Yin et al France, 2009	Assist us in our daily lives	A contextual mobile learning system framework	Allows us to learn mastering domestic and professional equipment
Schal et al. Austria, 2009	Field workers of utility companies in outdoor tasks	AR maintenance system	The work addresses these issues using spatial interaction and visualization techniques for mobile AR applications
Karhela, T Finland, 2008	Plant maintenances	Augmented Reality, video stream processing and human-technology interaction.	The concept involves video-stream based user interfaces, mobile devices and location-aware information services.
Billinghurst et al. USA, 2008	Assembly work	Mobile phone based augmented reality (AR) assembly system	Complex model information is located on a PC, and a camera phone is used as a thin client access device to augment still images of the assembly site with animated AR sequences
Mooser et al USA, 2007	Oil platform equipment maintenance system	Mobile clients to multiple data sources AR system	Collaborative, data-driven mobile application
Savioja et al. Finland, 2007	Industrial plants	Plant Model Services for Mobile Process Maintenance Engineer	For plant personnel or personnel of an industrial service provider

Andel et al Sweden, 2006	Engineering	Multiple collaborators can use consumer mobile camera phones to furnish a room together in an Augmented Reality environment	Interactive collaborative face-to-face Augmented Reality
Henrysson et al. Sweden, 2005	Engineering	Augmented Reality application for 3D scene assembly.	3D content can be manipulated using both the movement of a camera tracked mobile phone and a traditional button interface
Rios et al Mexico 2012	Aviation	Troubleshooting system with connection to AR maintenance system	System enables user to follow no linear procedures commonly found in fault isolation of aeronautical engines

Table 5 AR applications on Mobile/tablet hardware in the maintenance domain

In the next chapters the description of the EBAS system and its main functions will be introduced, also data from the Aeromexico company where an explanation of why the EBAS was chosen to be the center of the development then, in the next chapter, an explanation of the software in the mobile device will be described to reach the final part where the results and conclusions are presented.

Chapter 3 The engine bleed air system of the BOEING 737

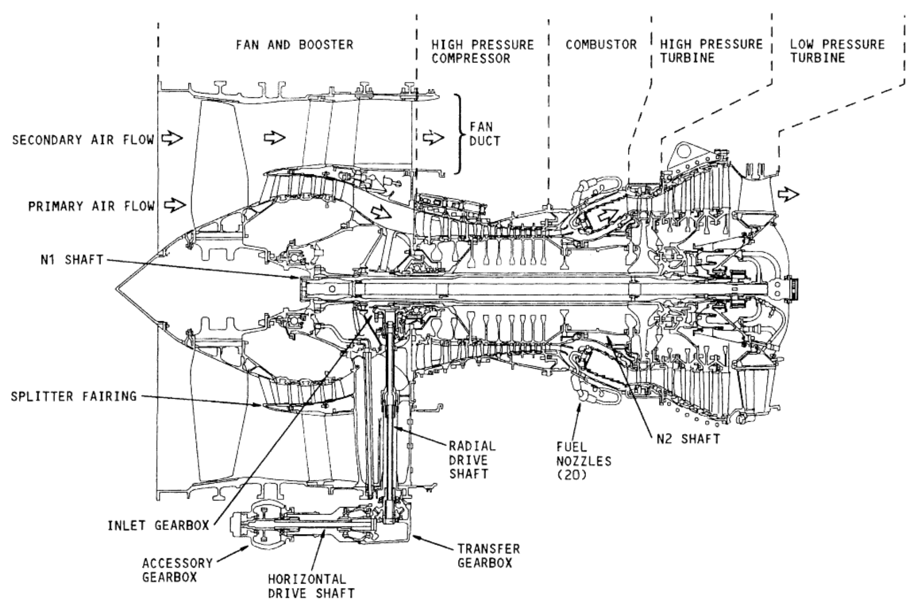
The BOEING 737 aircraft is equipped with two CFM56-7B engines that supply trust for the airplane. The engines also supply power for these systems:

- Electric
- Hydraulic
- Pneumatic

This work is centered in the study of the pneumatic system and this chapter is designated to give an introduction to the troubleshooting techniques and the maintenance procedures for the mechanical component that belong to the EBAS.

The 737 Engine Bleed Air System is designed to provide engine compressed air to air conditioning pack with the purpose of air pressurization in flight, engine air from the compressor is used, from the 5° and the 9° stage in a safe an economical way.

The pneumatic system takes air from the Engine 9th Stage Compressor (High Stage) at low throttle settings and the 5th stage compressor (Low Stage) at higher throttle settings.



CFM56-7 POWERPLANT GENERAL DESCRIPTION 72-3

Figure 12 Air is taken from the 5° and 9° stages of the compressor section [31]

During the different phases of flight the components must extract and regulate the air to achieve the expected requirements for the aircraft pressurization. The Bleed Air Regulator (BAR) controls the Pressure Regulator and Shutoff Valve (PRSOV) the purpose of the valve is regulate to **42+/- 8 psi,** this is the range of pressure where the system will function most efficiently

The 737 EBAS also control the temperature of the air this is accomplished by the precooler control valve (PCCV) and the precooler. The precooler is a heat exchanger that uses fan air to cool the hot compressor air, the valve controls the temperature from 390 °F to 450 °F (199 -232 °C).

The system also control which compressor air is been used, this could the 5° or the 9°. At lower engine speed N1, the system use 9° stage air because it can accomplish the requirements of the air conditioning packs; the 5° stage is too low at this phase. This regulation is done by the High Stage Regulator (HSR) and the High Stage Valve (HSV) to **32 +/-6 psi**. When the engine runs at higher speed and the air pressure gets above 32 +/-6 psi the HSR closes the HSV and the system operates at the 5° stage engine air.

When the system pressurization drops below **32+/-6 psi** the HSR opens the HSV and the 737 system operates in the 9° stages engine air. The check valve was placed in the design to prevent reverse flow when the air is taken from the 9° stage as shown in Figure 13. When the air pressure of the 9° stage is equal or greater than the 5° stage, the HSR causes the HSV to close in this way reverse flow is not permitted for the 9° stage.

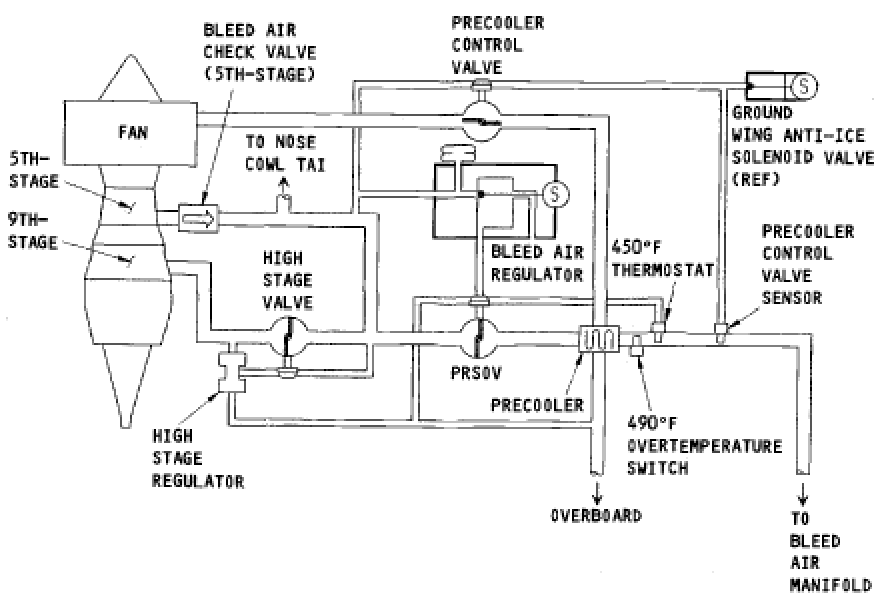


Figure 13 Pneumatic system schematic [28]

In the other hand if the temperature reaches 490°F there is a overheat switch that closes the PRSOV.

The 737 Bleed air system is design to the following:

1. Regulates engine bleed air to 42 +/-8 psi
2. Regulates engine bleed air temperature to 390-450 °F
3. Control 5 and 9 stage air to accomplish systems requirements
4. Prevents reverse flow to the engine compressor
5. Prevents the engine bleed air from getting hotter than 490 F

Description of subsystem in the EBAS

When the system is working in the high stage regulation the components functioning are the HSR and the HSV (32 +/-6), the HSR is controlled only with pneumatic inputs, and this component turns off when reverse flow is detected. There is a supply pressure for the HSR that comes from the 9° stage, when the supply pressure is 10 psi the HSV will be open, when the supply pressure is higher, the HSR provides a constant pressure so the HSV can regulate to 32 +/- 6 psi. When the 9° stage compressor is greater than **110 psi** the HSR closes the HSV, also when reverse flow is detected from the PRSOV during engine start, the reverse flow diaphragm closes the HSV.

The check valve in the 5° stage prevents the reverse flow to the 5° stage, this component will keep safe the engine and without damage.

In other side after the PRSOV the precooler change the temperature of the air, using the fan air, the component is in charge of controlling the amount of fan air that enters is the precooler control valve (PCCV), the air conditioning pack functions more efficiently 390-400 °F, the idea is to control the engine bleed air by using the air from the fan, in the same fashion there is a supply pressure and control pressure in the PCCV, when the control pressure is at 10 psi the air is not flowing. The PCCV is controlled by a 390° sensor when the temperature gets above 390° the control pressure is reduce so the PCCV opens to let air flow. When the air temperature reaches 440° F the 390° is fully open causing the PCCV to be fully open. The supply pressure and the control pressure can be measure by a troubleshooting technique.

The BAR and PRSOV control the air pressure of the EBAS, the PRSOV is the last valve that will send the compressed air to the system, the BAR will close the PRSOV if overpressure is detected, there is a supply pressure to the BAR, then it will supply a control pressure to the PRSOV, this way the regulation is detected, when supply pressure is 10 psi PRSOV opens, if the supply pressure is higher the BAR supplies a control pressure so that the PRSOV can regulate to 42+/-8 psi.

If HSV fails and let the air from the 9° flow without control, the BAR has an overpressure switch that will close the PRSOV by reducing the control pressure to 0.

The overpressure switch will cause the bleed trip light to illuminate. If the 450° F is activated will reduce the control pressure for the PRSOV in order to regulate the amount of air that is passing through the PRSOV, this should allow the precooler to cool the air that is flowing, if the temperature keeps racing the 450° sensor will continue to close the PRSOV until the EBAS system pressure is really low.

A description of how the system works during the different phases of flight will be presented, in engine ground idle the high stage system will be providing the air, the check valve will be close and the air is at low pressure, the PRSOV will be fully open, the air temperature is low enough for the PCCV to remain close. At taxi the high stage system will most likely be providing the bleed air, depending on the throttle setting the pressure will be higher that 32 +/-6 psi, if this is the case the HSV will reduce the pressure also if the air is hotter than 390° the sensor will open the PCCV to cool it.

During takeoff and climb throttle settings the high stage air is too high, the HSR will close the HSV and the air will flow through the 5° stage to the PRSOV, the air pressure will be greater than 42 +/-8 psi therefore the PRSOV will regulate the amount of air entering the system also the temperature will be greater than 390° the PCCV will open to regulate the temperature.

During cruise the throttles are reduce to maintain speed, also the aircraft becomes lighter the low stage will go below 42 +/-8 psi, the HSV will be close. The PCCV will close because temperature is not above 390°. In some point the low stage air will be too low so the high stage pressure will enter the system until it gets to the maximum allowable pressure at the same time the air temperature may be greater than 390° and the sensor will activate the cooling system.

In decent the throttles are back to flight idle the HSV continues open, typically the pressure is less than 32 psi so the HSV will be completely open as the PRSOV, and also the temperature is below 390°. When an operator must troubleshoot the system, he uses simple test equipment that will lead to the component that has failure, this equipment consist in hoses, fittings, regulator, nitrogen pressure source, T-valve and gauge. The procedures have been developed to monitor the pressure depending of the reports of failure by providing nitrogen to HSV, PCCV, HSR and PRSOV.

Maintenance

Maintenance strategies can be broadly classified in two types: the corrective maintenance (CM) and preventive maintenance (PM). In the industry application of the PM strategy can be generally performed through either experience or original equipment manufacturer (OEM) recommendations, and is based on a scientific approach, where in most cases it is performed at regular time intervals, T [32]. This is the case of the aviation industry, airlines like Aeromexico, it must provide PM to the aircrafts and when the components fail the company will run the corrective maintenance to certified health of the machine and security for the passengers. There are also other concepts involve in the maintenance area that are applied in the aviation industry like the time-based maintenance (TBM) and condition-based maintenance (CBM). As shown in Figure 14 the general TBM process is based in the failure data analysis and it also assumes that the failure of the equipment is predictable

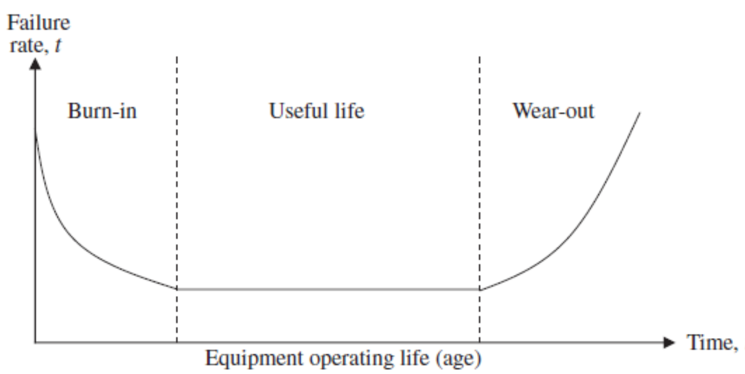


Fig. 1. Bathtub curve.

Figure 14 General TBM process [32]

CBM was introduced in order to minimize cost of maintenance because in some cases it is very difficult to obtain an assessment for the TBM that will maintain low the cost and the equipment in good conditions. Figure 15 show the process for CBM, as its name suggest condition monitoring is based on special measurements devices, such as vibrations, pressure gauges and others. The CM process can be carried out into two ways: on-line and off-line. On-line processing is carried out during the running state of the equipment (operating state), while off-line processing is performed when the equipment is not running. [32].

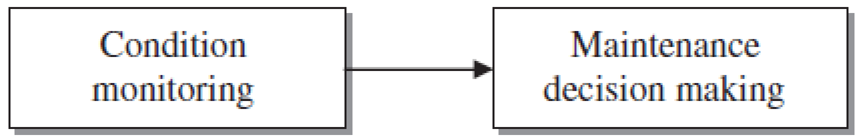


Figure 15 General CBM process [32]

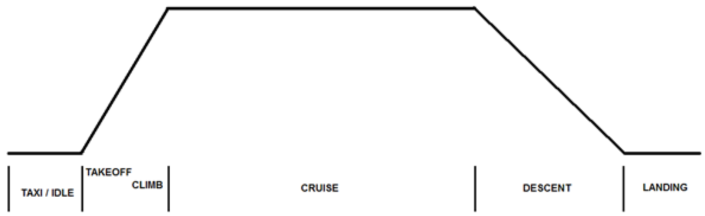
The principal maintenance tasks that where included during the stage of development of the software are the following:

- Chapter 36 Pneumatic Fault Isolation Procedure
- TASK 36-11-03-000-801 BLEED AIR REGULATOR – REMOVAL
- TASK 36-11-03-400-801 BLEED AIR REGULATOR – INSTALLATION
- TASK 36-11-04-000-801 PRESSURE REGULATING AND SHUTOFF VALVE (PRSOV) – REMOVAL
- TASK 36-11-04-400-801 PRESSURE REGULATING AND SHUTOFF VALVE (PRSOV) – INSTALLATION
- TASK 36-11-05-000-801 450 F THERMOSTAT - REMOVAL
- TASK 36-11-05-400-401 450 F THERMOSTAT – INSTALLATION
- TASK 36-11-06-000-801 HIGH STAGE VALVE - REMOVAL
- TASK 36-11-06-400-801 HIGH STAGE VALVE – INSTALLATION
- TASK 36-11-07-000-801 HIGH STAGE REGULATOR - REMOVAL/INSTALLATION
- TASK 36-11-07-400-801 HIGH STAGE REGULATOR – INSTALLATION [33]

Each of the tasks have specifications of the references that the user have to use, the tools, the proper disassembly process, the tags that must be placed to avoid injury and it also specifies the torque of each screw in the component for the installation process.

Isolation of faults

Typically the pilot reports are of two types, one when the bleed trip light was illuminated and the other one is for low duct pressure, the personal in charge of maintenance have to process the available information like the phase of flight, pressure of the ducts, N1 revolutions of the engine, altitude among others. If some of the information is not like available like N1, the maintenance operator has to get the information by running the engine.



Taxi / Idle – Low throttle settings   High Stage Air

Takeoff / Climb – Very high throttle settings   Low Stage Air

Cruise – Throttles continually are reduced during cruise.   Low Stage may crossover to High Stage

Descent – Throttles are at flight idle High Stage Air

Figure 16 Stages of flight

The main task for the isolation procedures are:

- BLEED TRIP OFF Light On for both engines
- Bleed valve: does not close when the bleed switches are moved to off, the engine is the bleed source.
- Duct pressure indication: high, low or zero, the engine is the bleed source.
- Isolation valve: does not operate correctly.
- Duct pressure indication: L and R pointers not the same (split), the engine is the bleed source.
- Duct pressure indication: L and R pointers not the same (split), the APU is the bleed source.

A brief description of the procedures will be given in the following section, the reader should be aware that due to the fact that sensitive information is treated, the procedures will be described general terms.

BLEED TRIP OFF Light On for both engines

Occurs when the Precooler outlet temperature is above 485-500 °F (252-260° C) but it also can occur when an overpressure condition is detected (250 psi for the upstream in the PRSOV).

Bleed trip due to overpressure do not occur often and they are typically in takeoff thrust. But the over temperature condition is typically due to the PCCV not opening sufficiently.

The typical causes for overpressure are the HSV not fully close, the HSR providing too high control pressure to the HSV or faulty BAR overpressure switch actuating too early. If there is an overtemperature could be due to the PCCV, 390° sensor does not open correctly, 450° sensor does not open correctly or the Precooler is not effective.

Bleed valve: does not close when the bleed switches are moved to off, the engine is the bleed source

This condition is presented when the switches are moved to off position but the pressure indication of the dual duct does not decrease to less than 10 psi.

A typical failure is presented in the harness when they have an internal shorting that can cause that the electrical array does not close the PRSOV.

Duct pressure indication: high, low or zero, the engine is the bleed source.

A high duct pressure condition is a condition in which one or both pointers on the dual duct pressure indicator are higher than 50 psi, with the engines as the bleed source when operating on regulated 5th stage pressure in a stabilized condition. If you have a pilot report or an observed fault and you know the bleed pressure, engine N1 speed, and the altitude at the time the fault was observed, you can determine if the system was operating within limits.

A low duct pressure is presented when one or both pointers on the dual duct pressure indicator are lower than 34 psi. It can be difficult to tell which part might be causing the problem when so many parts affect low duct pressure, the idea is to isolate the part by using the proper troubleshooting equipment like nitrogen source, hoses and regulators, and this equipment is used to simulate the effects of the different pressures in the valves. If you know the phase of flight and have the information of the pressure it can be determined if the engine was running within the limits with N1 vs altitude graphs.

Isolation valve: does not operate correctly.

The isolation valve is controlled by a three-position switch on the P5-10 panel, this is also electrically connected to four switches: engine no 1 bleed switch, engine no 2 bleed switch, left pack switch and right pack switch.

The APU bleed air APU bleed air or bleed air from an external ground air source may be used to determine if the operation of the isolation valve is correct.

Duct pressure indication: L and R pointers not the same (split), the engine is the bleed source.

Split duct pressure is a condition in which the duct pressure on one side, as shown on the dual duct pressure indicator, is either lower or higher than the duct pressure on the other side with the engines as the bleed source.

If the pilot report contains all of the necessary information to use either one of the graphs, a system test using the engines may not be necessary to determine if one or both systems have faults, if the information is not provided the function of the system can be check by using the proper equipment. Duct pressure splits do not always indicate a fault condition.

Duct pressure indication: L and R pointers not the same (split), the APU is the bleed source.

Split duct pressure is presented when the duct pressure on one side, as shown on the dual pressure indicator, is lower or higher when compared the other side when the APU is the only bleed source and the isolation valve is open, this pressure should be the same.

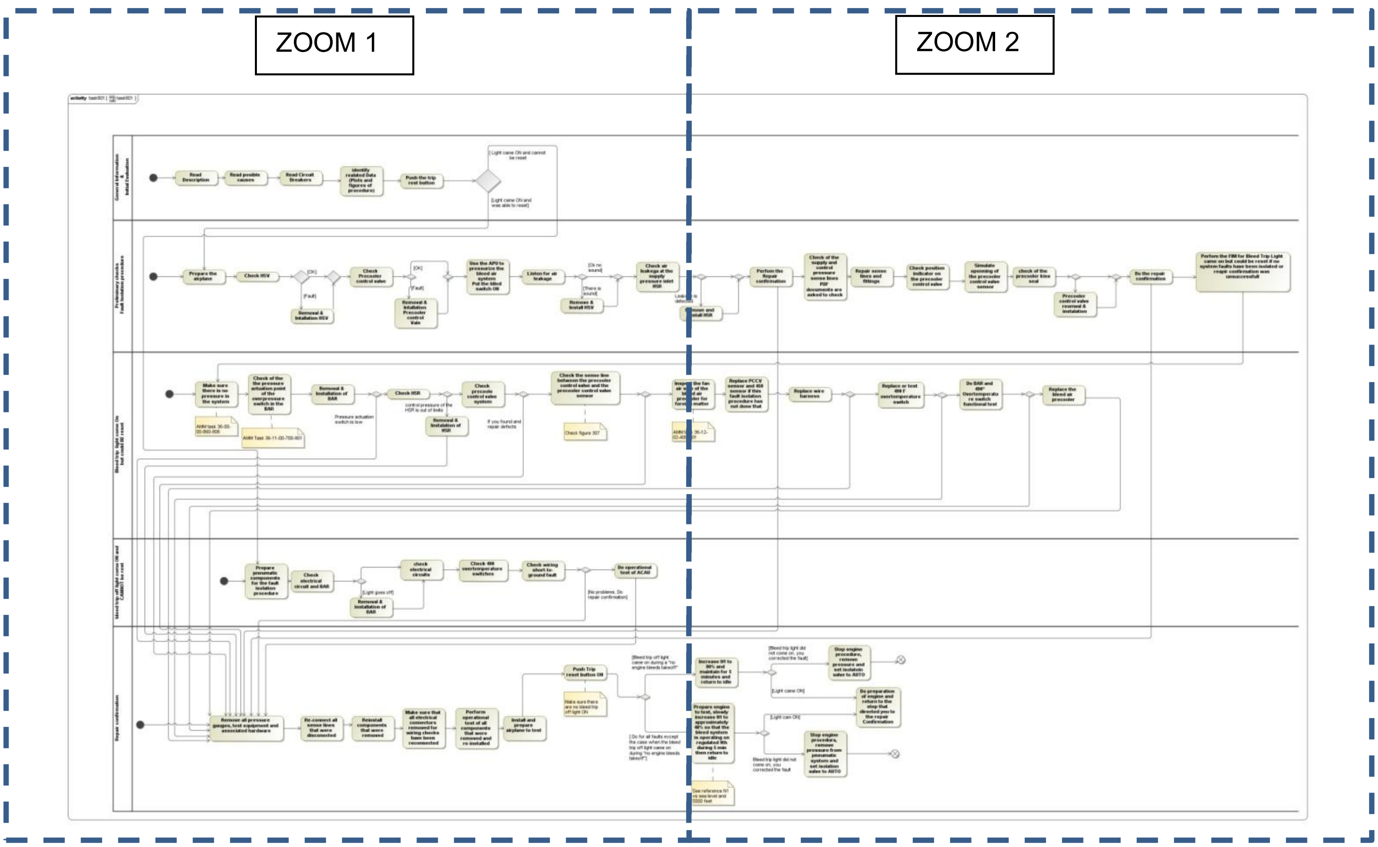


Figure 17 UML Activity diagram of TASK 801

Figure 17 shows an example of the isolation process that the operator must follow to isolate the fault, every procedure is presented in printed paper.

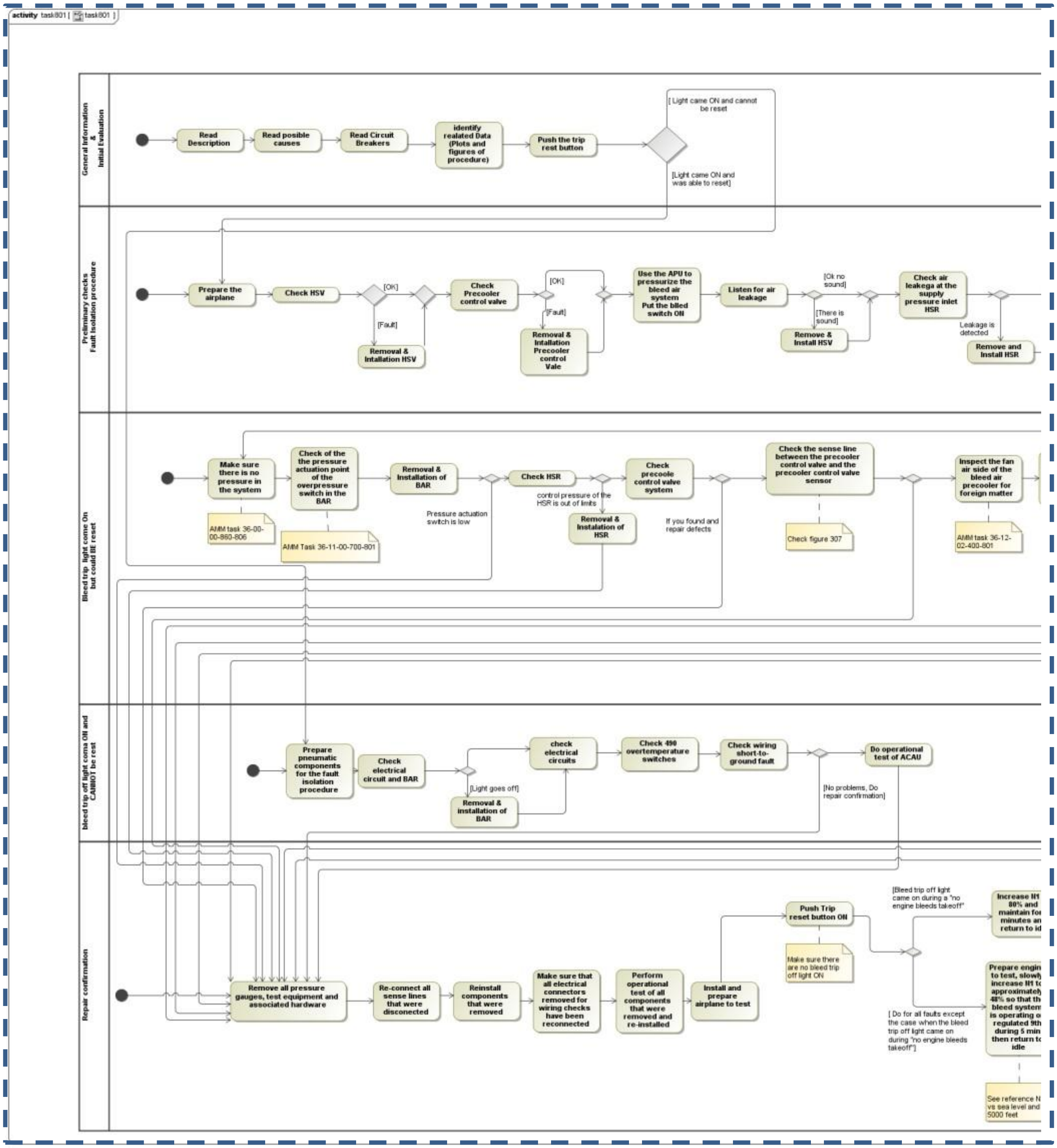


Figure 18 Zoom 1 UML Activity diagram of TASK 801

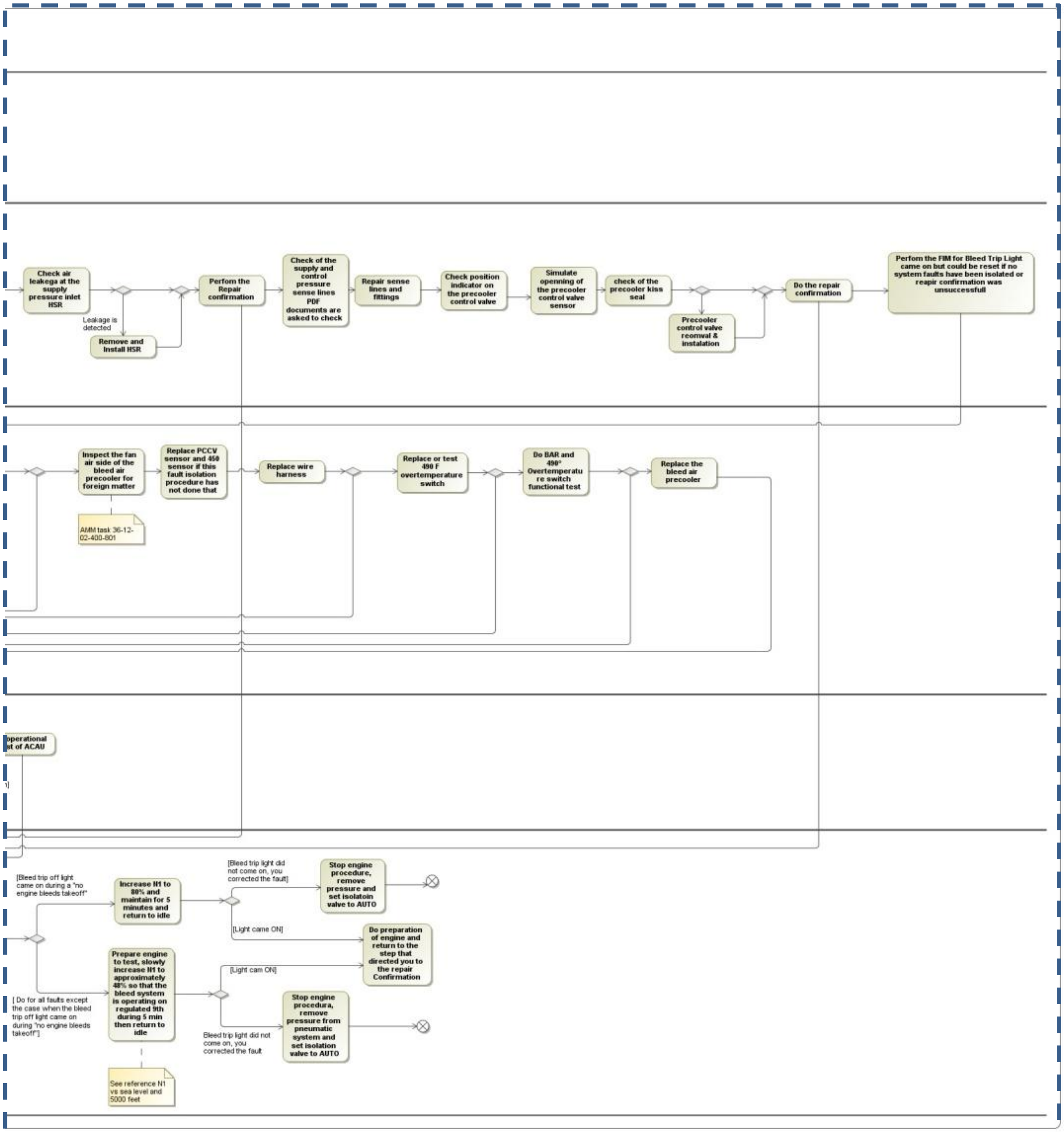


Figure 19 Zoom 2 UML Activity diagram of TASK 801

Chapter 4 Software development

In this chapter a detailed description of the development of the software is presented, the major components will be discussed and the different problems that were passed to obtain the final version of the software for maintenance procedures and troubleshooting techniques on mobile devices.

The game development engine that was chosen is UNITY 3D, due to the advantages that offers. The main reason of the decision of choosing this tool was the capability to export to several operating systems with few changes, this way the code of the application was created in such a way that the main program could be built for iOS and Android operating system.

In the following table a review of the main characteristics of the game engines that include capabilities to develop AR applications, as shown the one that accomplish more positive point was the UNITY game engine.

Game development engine	Advantages	Disadvantages
Unity game engine	- Lower cost compared with other game engines ($5000.00 USD vs $20,000.00) - Capable of building project to different operating systems (Android, iOS, web, PC, web, flash, xbox, ps3, wii) -Easy to start developing - Very intuitive thanks to the graphical / coding interface - It was designed to support connection with design software (3dsmax, Maya) - Capable of updating files in the moment they are changed	- Hard to connect with other programs with plugins - Hard to master programming abilities -Some memory issues in the Graphical User Interface for mobile devices
World Viz Vizard	- Specialize in virtual environments and starting with AR - Good customer care	-Cost over $25,000 USD -Not very stable according to the test in trial full version
Xcode	- Native programming for iOS	-Only works for iOS

Eclipse	- IDE for native programming for Android	-Only works for Android

Table 5 Comparative between different game engines with AR capabilities

The plugins that were imported and use to provide the augmented reality libraries was VUFORIA belonging to the company QUALCOMM; these libraries are compatible with both mobile operating systems. It is worth to mention that there are no license fees or royalty payments required for the use of the Qualcomm AR SDK for development or distribution of commercial applications [34].

In the Table 6 the different tools employed to the development of the software are described, the output of the project is an .APK file that can be installed in the tablets with android system for the iOS system a developer account is necessary to install the software without putting it in the app market, it is worth to note that the software cannot be in the markets for mobile systems because of the sensitivity of the information manage in the project.

Tool	Type	Description of use
IMAGEJ	Freeware	Measuring images with reference dimensions
CATIA V5 R21	Software	Modeling of the pieces that will be used in the AR animation. Specify correct dimensions.
3DSMax	Software	Give texture render and animation to the assembly processes
Unity 3D	Software	Create the interface with the necessary elements to work with AR and the Graphical User Interface and the Human Machine Interface (scenes, camera, tracking, scripts, buttons)
Motorola XOOM	Hardware tablet	Work with the AR application Manage the current scene, size and position of animations, deploy of the Fault Isolation Software
Galaxy tab 10.1	Hardware tablet	Work with the AR application Manage the current scene, size and position of animations, deploy of the Fault Isolation Software
Ipad 3	Hardware tablet	Work with the AR application Manage the current scene, size and position of animations, deploy of the Fault Isolation Software

Table 6 Tools used to build a project with AR in mobile technology

3.1 Software architecture

In the present section the architecture of the software that was developed is presented, the four types of diagrams that are included from the Unified Modeling language commonly used in software design:

- Class diagrams describe the types of objects in the system and the various kinds of static relationships that exist among them. The boxes diagrams are classes, which are divided into three compartments: the name of the class, its attributes, and its operations.
- Use Cases are used to capture the functional requirement of a system; they describe the typical interactions between users of a system and the system itself, providing a narrative of how a system can be used.
- State machine diagrams are a familiar technique to describe the behavior of a system.
- Activity diagrams are a technique to describe procedural logic, business process, and work flow.
- Sequence diagrams describe how groups of objects collaborate in some behavior. It captures the behavior of a single scenario. [35]

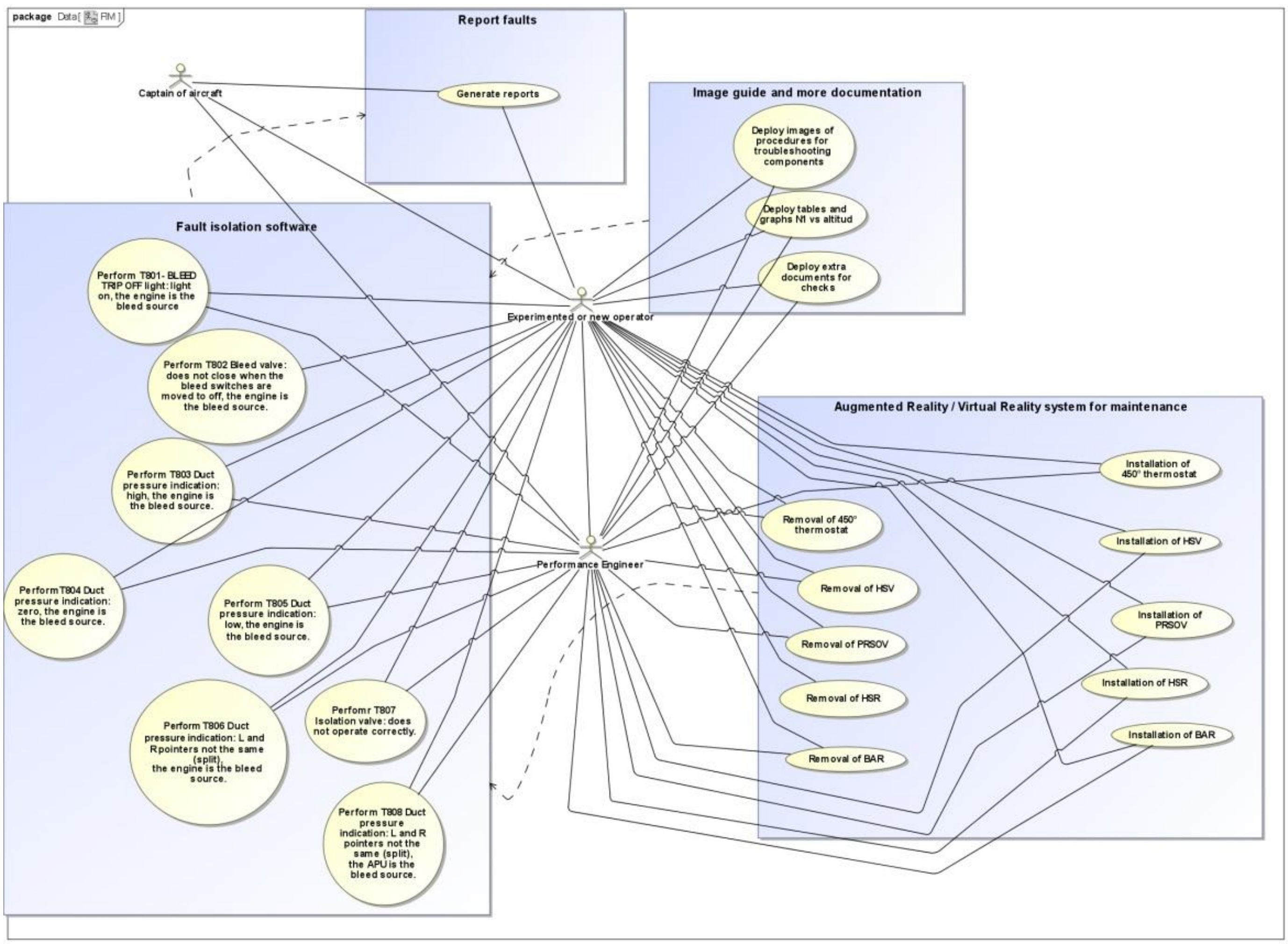


Figure 20 Use case diagram for the software

In Figure 20 are defined two main users of the system, the operator (new or experienced) and the performance engineer who is charge of the health of the aircraft, the software must provide easy access to all the components independently, the isolation and maintenance procedures can be access from different interfaces to maintain an horizontal line of knowledge where the user is capable of retrieve the necessary information to perform an identified task. The third actors shown is the captain who triggers the procedures by sending the fault message, this actor will not access the tablet because his labor is to properly document the fault in one independent system that will be connected to the isolation software.

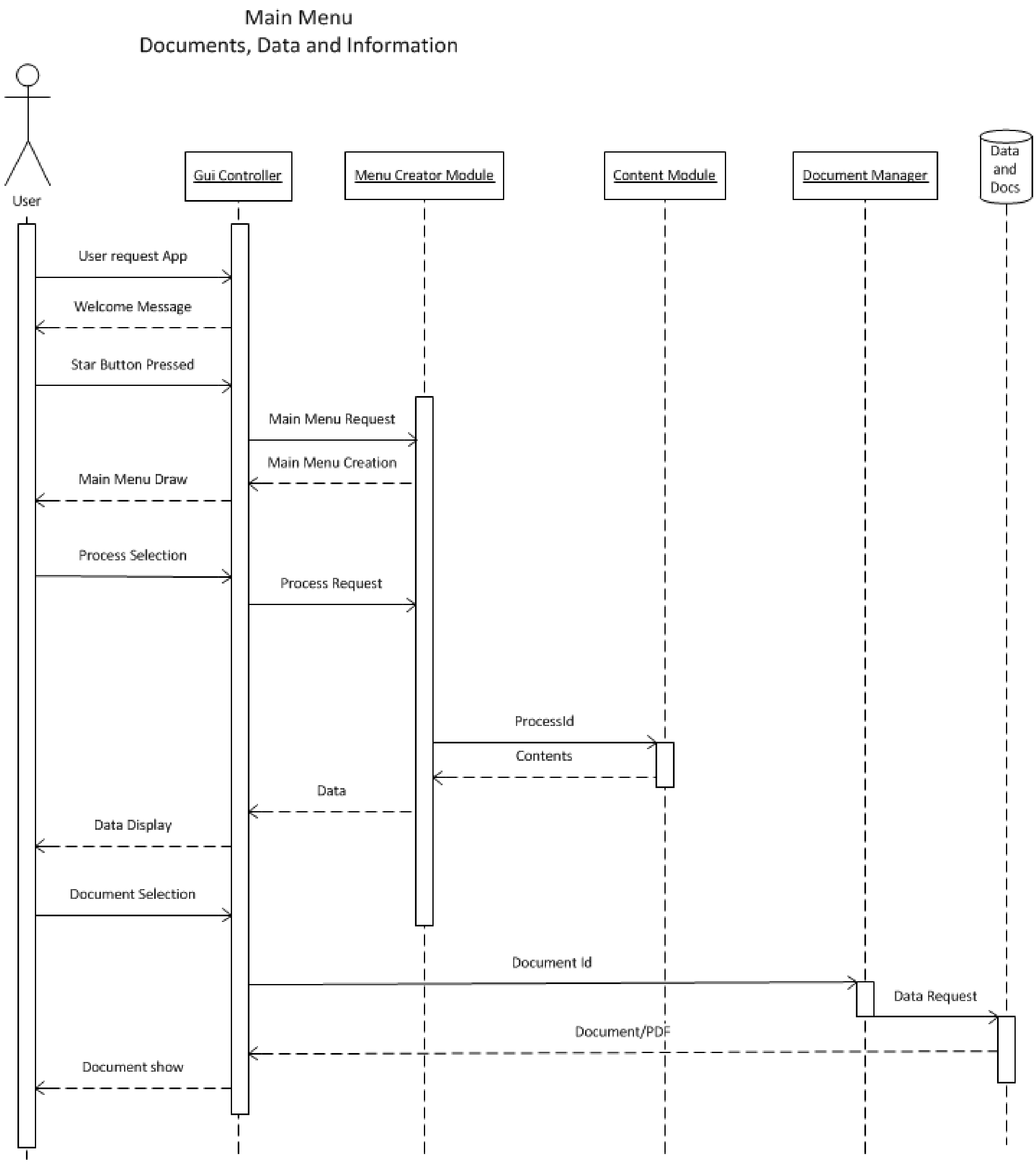


Figure 21 Sequence diagram for accessing the main menu of Fault Isolation Procedure

The system can be access from various graphical interfaces, Figure 21 shows one case where the user start the isolation process by choosing the procedure and deploying the written instructions and informational tables to quickly troubleshoot the fault in the engine. The interaction is accomplished by buttons and zooming tools in the tablet.

When the user needs to start the removal or installation of procedures, he must call the subsystem by two different methods from the isolation system or enter directly to the AR system, the interactions in this part are made in three different events in the tablet, that are defined as the gestural interface in the system, one finger touch to travel around the system and choosing the right procedure also this event will rotate 3D models when the AR is been deployed, two fingers touch to zooming the 3D models in case the user needs to access small details in the aircraft components and three fingers touch to jump from step to step in the removal and installation procedures, Figure 22 represent how this gesture capabilities are used in the tablet system.

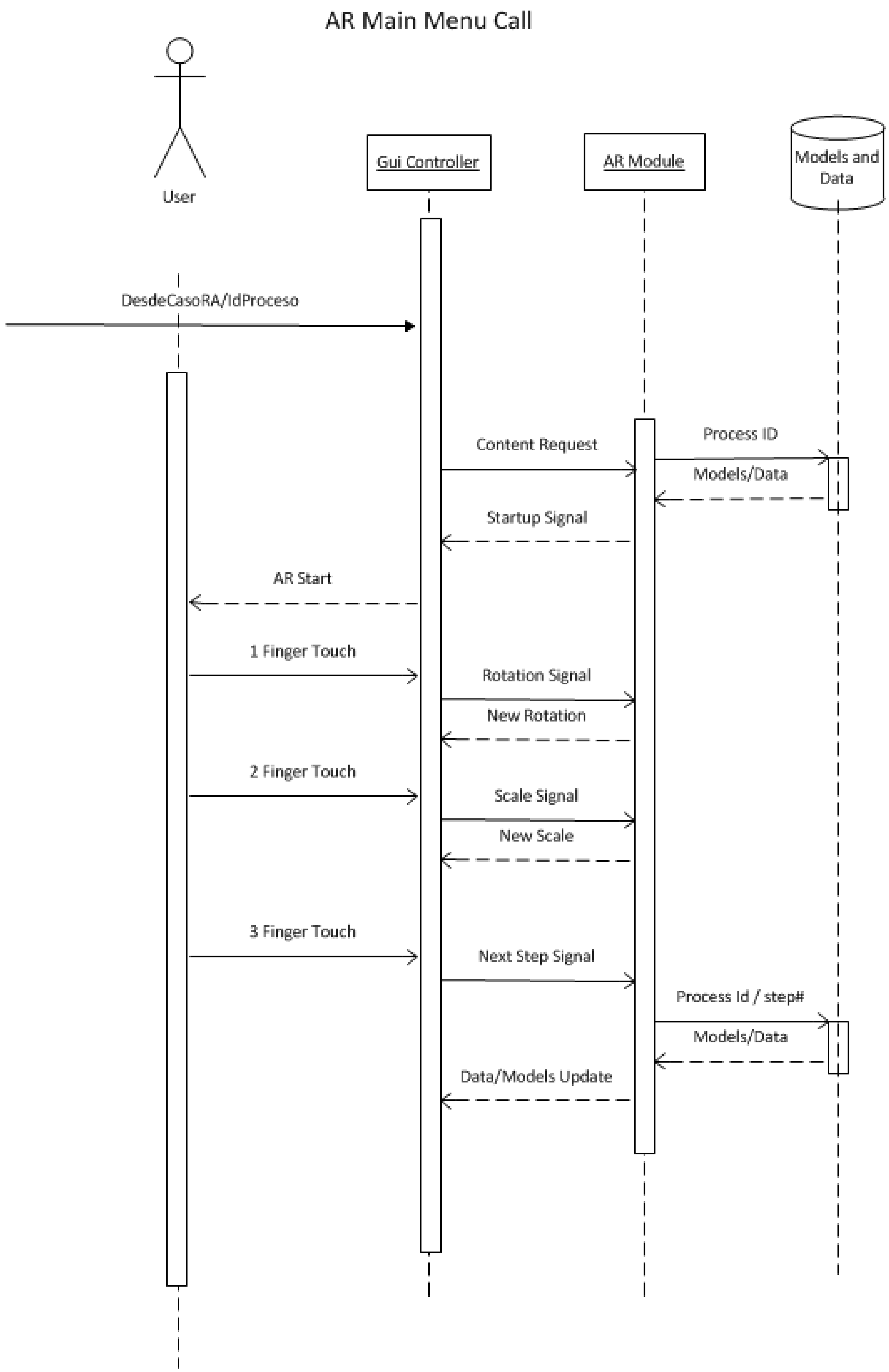


Figure 22 Sequence diagram showing the calls for AR procedures

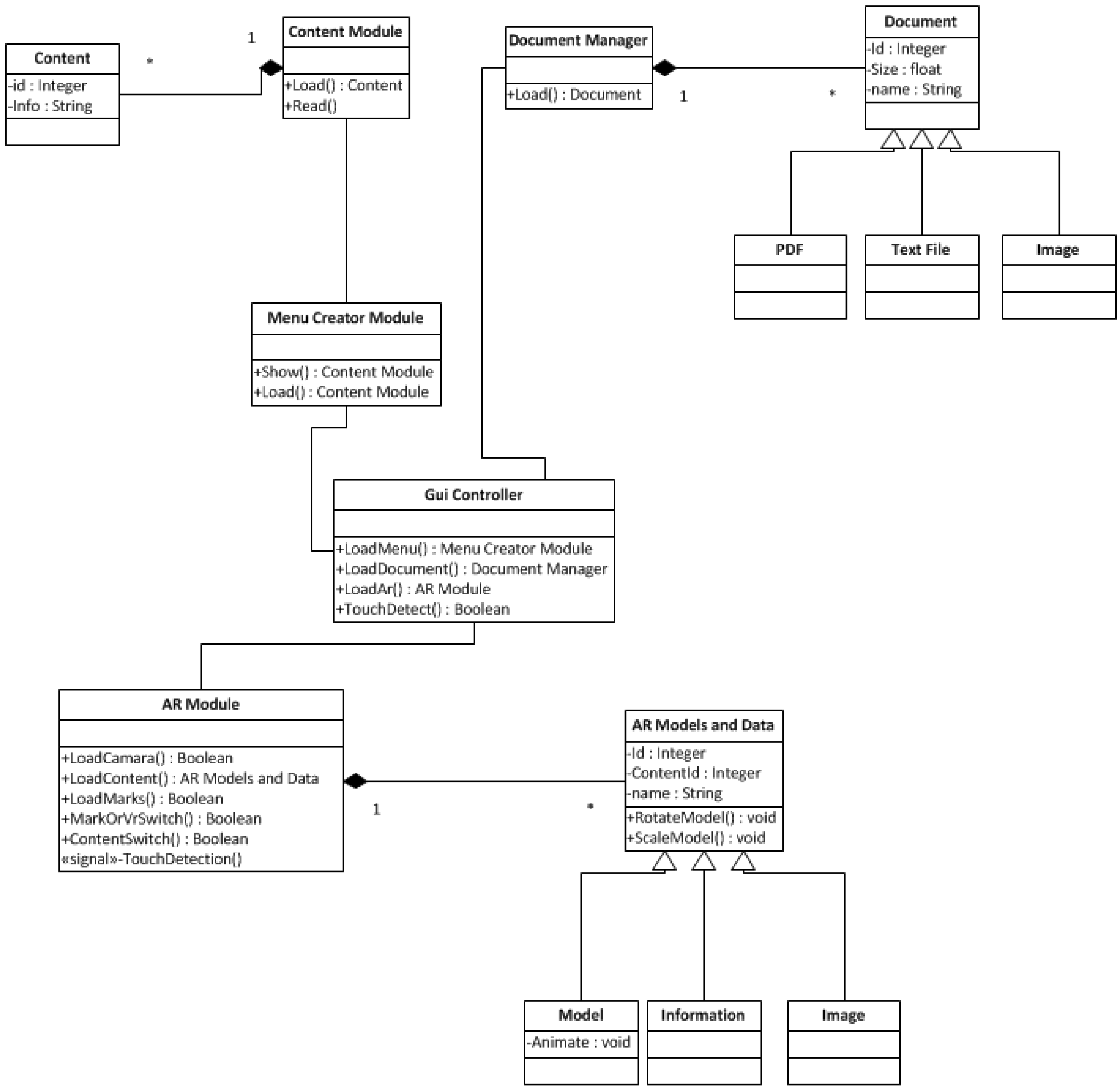


Figure 23 Class diagram of the Fault Isolation Software

Figure 23 explains in a general approach how the classes in the system are connected to deploy different kinds of information in the Fault Isolation Software like AR/isolation/images modules; the main class GUI controller is in charge of the rendering of all the components and it will load the proper documentation for each use case presented in Figure 20.

Fault Isolation software development

As shown in the previous section (see Figure 20 for reference) the main system that calls the removal and installation of components is the Fault Isolation Software. It was developed in an iterative way for two reasons, first testing the capacities of the tablet to hold all the information needed to perform the troubleshooting task efficiently and second the point of view of the costumer, in this case the airline, to evaluate that the software is representative of the procedures according to the aeronautical norms and regulations.

The Fault Isolation Software main function is to deploy information of the troubleshooting task in a timely manner but also it is linked to .txt files that can be updated every time that the current manual from BOEING company changes. This system allows mail communication from the user to other people involve in the repair of the engine and it also can access documentation in pdf format to deploy other manuals that are not included in the scope of this project but in the future the expansion to other tasks is designed.

Augmented reality System development

For the part of the system where the removal and installation of components is presented, the AR technology became a great opportunity to deploy the content to enhance operator ability of troubleshooting the EBAS. In the next section explains how this subsystem was created to accomplish the goals of the present project.

Phases of AR development

1. Design

   In this stage the requirements, scope, connection with other systems in this case the Fault Isolation Software where taken into account, due to the fact that tablets technology has lower capacities than desktop computer; the design of the administration of the memory was crucial for the system.

2. Collect information associated with each task and identify crucial steps for AR

The company provided the know-how of the maintenance tasks to remove and install components in the correct way, the hidden details that come from experience were documented to provide a better understanding of the AR manual, capture this details was the principal objective of this phase.

3. Collect dimensional information of components in the hangar

When the design stage was over, the list of the principal components was release, measuring the components to reproduce them virtually (CAD 3D model) was the next step. Due to the fact that the components were restricted to the hangar, a process to capture data was implemented, also the team counted with only 1 day to gather all the necessary data for the modeling stage.
Pictures in the principal planes of the components were taken with appropriate reference dimensions also some sketches were done with measure dimensions of the components, later the freeware IMAGEJ was used to process the photographs to obtain all the necessary dimensions to produce the 3D model with the help of the notes taken during the time in the hangar.

Table 7 Stage of collecting dimensional information of the engine

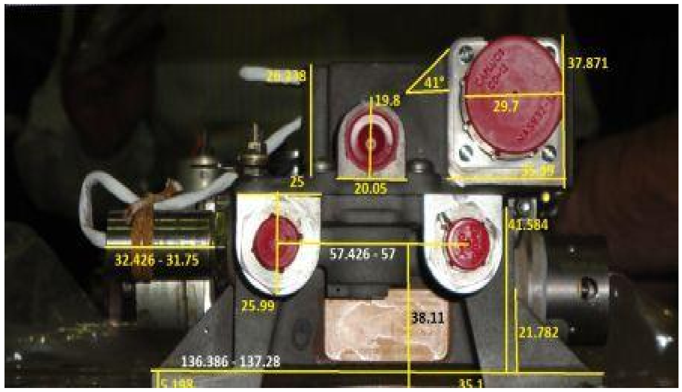


Table 8 Processing photographs with freeware IMAGEJ

4. CAD modeling

   After the dimensions were process with IMAGEJ, the software CATIA V5 was used to create the 3D model, due to the fact that the AR technology works with reference models, an approximation within +/- 5 mm to the real dimension of the part was good.

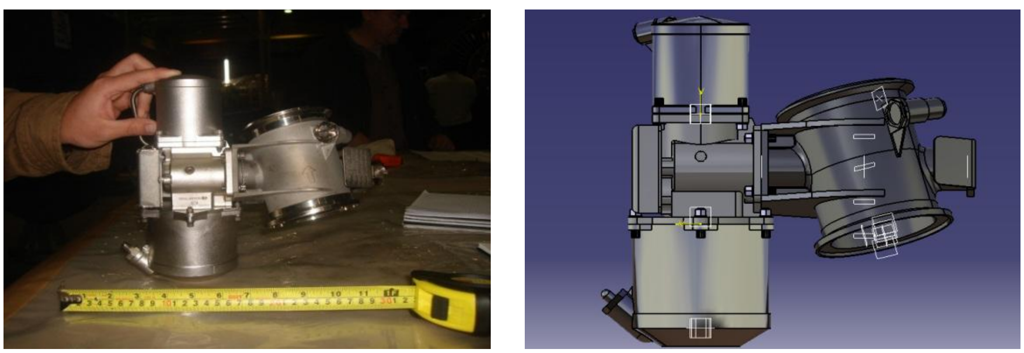


Figure 24 Results of the modeling stage of the project

5. Animation and texturizing of components

   The visualisation of the AR content plays a primary role in the enhacement of the user view, the textures and animations were fabricated using the software 3DSMAX from autodesk to make it look as real as posible, if the components look alike, the new maintenance operator is going to identify faster the components no only by shape but also by color.

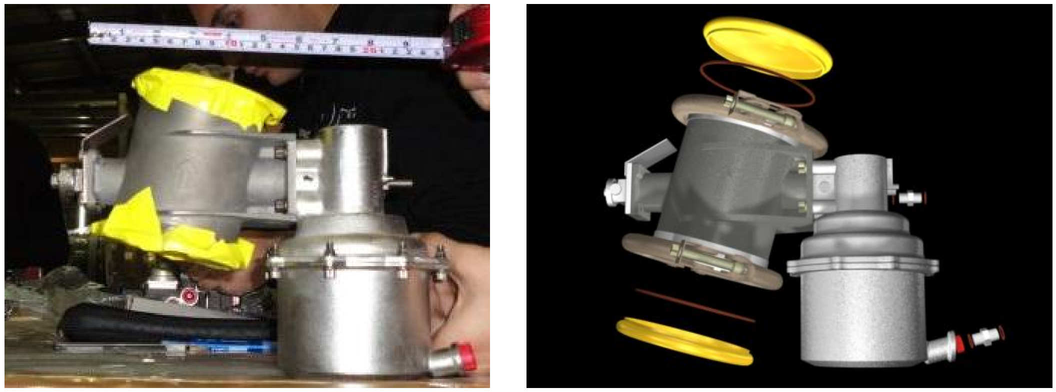


Figure 25 Real and virtual content before (left) and after (right) texturizing and animation stage

6. Programing of the system integration

   Although this stage began since the design of system phase, only until the models and animations are done the programmer can test the development, the system was divided in 10 scenes one for each task of removal and installation, the memory is completely clear between the jumps of scenes and for the particular case of one removal or installation task, memory was manage to only deploy one model with their respective text or helpful images, the background memory was no loaded with any invisible data to efficiently go through the steps of the manual, at the next step a new model is loaded and the old one is destroy.

Chapter 5 Discussion and results

The intention of this chapter is to report the results and finding of the investigation questions presented in chapter I, recalling:

Is this new tool going to improve the quality of training and troubleshooting the engine? The hardware is reliable enough to maintain the information with easy access at any moment? And from the perspective of the users, are they going to be willing to use the system?

This section is also dedicated to summarize the technical results of the software developed to formally present the solution proposed for the improvements in the troubleshooting and maintenance procedures of the pneumatic system of the BOEING 737. In the Figure 26 the hardware for the system designed in this work is shown, for the Augmented Reality part is only active when the operator has the scale prototype engine, where the components and procedures will be augmented in the real environment in proper scale, in case that the operator needs to take the tablet with him to troubleshoot the EBAS in situ, the system will persist in the virtual environment to guide the operator through the procedures.

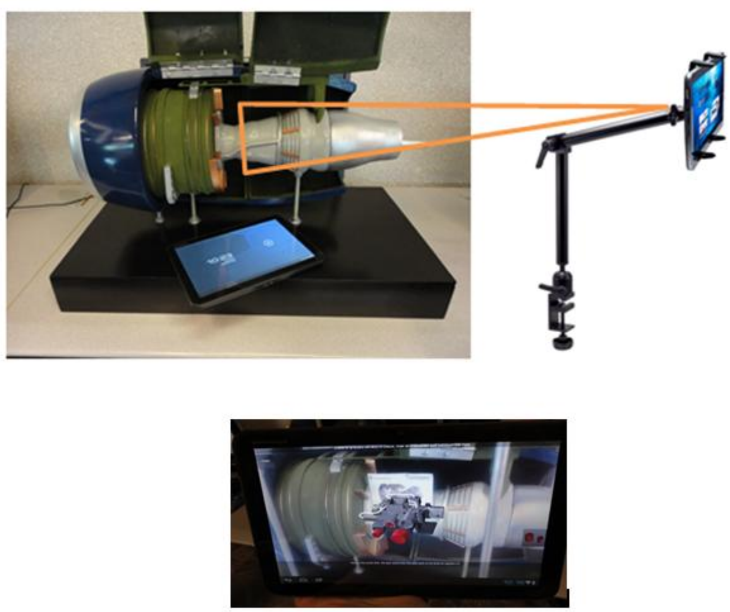


Figure 26 Industrial tablet holder to increase the ergonomics of the training system

Results of the software

The Fault Isolation Software was developed by an iterative process that made it possible to easily accommodate changes and also receive feedback from the airline to adjust the risk factor of finishing on time and adjust the process of creating the software dynamically [36].

The development process was divided into several iterations where representative parts of the system were reproduce, constructing only partial results for each iteration and also in each step an overcome of the game engine learning curve was attained.

Two major systems were developed, in one side the main system that controls the troubleshooting of the engine, it deploys the information according to the need of the user (refer to chapter II), from the main system the Augmented Reality subsystem is called to deploy the removal and installation procedures for the aircraft, the subsystem is designed to show the details that experienced operators know from the everyday procedures. In Table 9 the number of written lines of code is shown to deploy all the cases and procedures of the fault isolation manual, this system takes all the information from .TXT files to allow the users to change the data from the procedures every time that is needed, the system is design to be in constant evolution like the pdf manuals of the BOEING company.

Name of script	Number of code lines
Home FIM	175
Task 801	1093
Task 802	189
Task 803	939
Task 804	1045
Task 805	871
Task 806	650
Task 807	584
Task808	846
TOTAL FIM	6217

Table 9 Number of code lines generated for the Fault Isolation Software

In Table 10 is shown that 4179 lines were written to deploy correctly the AR system, with touch capabilities of every interface, like two, three and one finger detection to perform operations of drag, zoom and next step, also the memory manage to load and unload models depending of the task is include. Since the AR library was obtain from QUALCOMM [34] those lines are not summarize in this work, but the reader should notice that there is processing in the background of the software related to tracking of the image target and the scale/position of the 3d models.

Generic Scripts	Number of code lines
touch case	90
Main menu	36
PRSOV	
Home	23
Installation	614
Removal	413
BAR	
Home	35
Removal	306
Installation	334
HSR	
Home	32
Installation	507
Removal	268
HSV	
Home	31
Installation	518
Removal	354
Thermostat	
Home	25
Installation	332
Removal	261
Total for AR system	4179

Table 10 Number of code lines generated for AR maintenance procedures

In Table 11 the representative interfaces of the software is shown, depending of the fault the user will decide which interface will access first, the system is prepared to give easy access to any part of the system in less than 5 touches that would include the 8 isolation tasks, 5 removal and 5 installation tasks of components. This representative interfaces were classified with letters to facilitated their analysis; in the next section the statistics of performance of the tablet are presented.

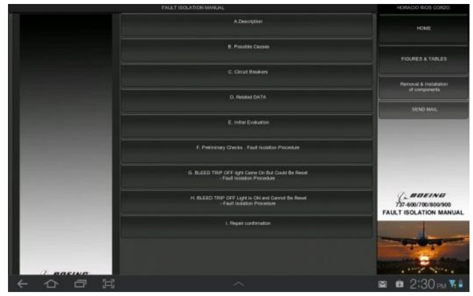
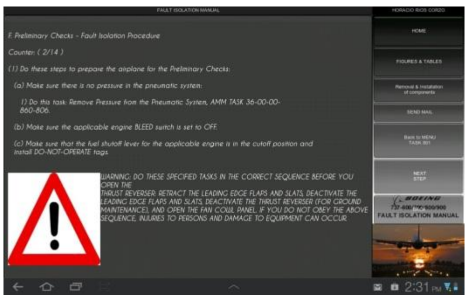
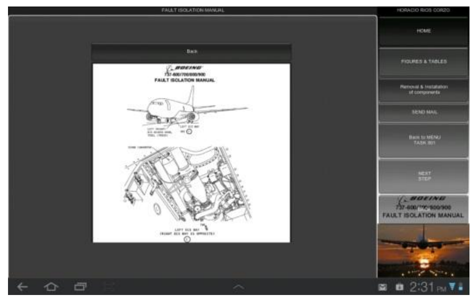
Graphical User Interface	
A  Menu of task in the isolation process	B  Submenu of procedures in the isolation process
C  Information deployed in the isolation process (the software is design to detect caution and warnings)	D  Guide images shown when needed
E  Quick acces to removal & installation procedures	F  Main menu of removal & installation
G  AR system showing visual information	H  System been used for training

Table 11 Graphical User Interface of mobile software

Before jumping to the analysis of the results some definitions are need it, for the different variables of the performance that can be measured, the statistics window for rendering contains the following information [37]:-

- **Time per frame and FPS.** The amount of time taken to process and render one game frame (and its reciprocal, frames per second). Note that this number only includes the time taken to do the frame update and render the game view; it does not include the time taken in the editor to draw the scene view, inspector and other editor-only processing.
- **Draw Calls**. The total number of meshes drawn after batching was applied. Note that where objects are rendered multiple times (for example, objects illuminated by pixel lights), each rendering results in a separate draw call.
- **Batched (Draw Calls**). The numbers of initially separate draw calls that were added to batches. "Batching" is where the engine attempts to combine the rendering of multiple objects into one draw call in order to reduce CPU overhead. To ensure good batching, you should share materials between different objects as often as possible.
- **Tris and Verts**. The number of triangles and vertices drawn. This is mostly important when optimizing for low-end hardware
- **Used Textures** The number of textures used to draw this frame and their memory usage.
- **Render Textures**. The number of Render Textures and their memory usage. The number of times the active Render Texture was switched each frame is also displayed.
- **VRAM usage**. Approximate bounds of current video memory (VRAM) usage. This also shows how much video memory your graphics card has.
- **VBO total**. The number of unique meshes (Vertex Buffers Objects or VBOs) that are uploaded to the graphics card. Each different model will cause a new VBO to be created. In some cases scaled objects will cause additional VBOs to be created. In the case of a static batching, several different objects can potentially share the same VBO.
- Visible Skinned Meshes The number of skinned meshes rendered.
- Animations The number of animations playing.

The Memory area displays some memory usage data [38]:

- Total Allocated is the total RAM used by the application. Note that in the Unity Editor this is memory used by everything in the editor; game builds will use much less.
- Texture Memory is the amount of video memory used by the textures in the current frame.
- Object Count is the total number of Objects that are created. If this number rises over time then it means your game is creating some objects that are never destroyed.

Name of subsystem or GUI	Statistics and observations of the software performance	
	Rendering	Memory
A – Menu of Fault Isolation Software	Draw Calls: 26 Tris: 1.6k Verts: 3.7k Batched Draw Calls: 0 Batched Tris: 0 Batched Verts: 0 Used Textures: 0 / 0 B RenderTextures: 0 / 0 B RenderTexture Switches: 0 Screen: 64x64 / 48.0 KB VRAM usage: 48.0 KB to 145.2 KB (of 256.0 MB) VBO Total: 12 - 97.2 KB VB Uploads: 0 - 0 B IB Uploads: 0 - 0 B Shadow Casters: 0 Visible Skinned Meshes: 0 Animations: 0	Total: 14.0 MB Delta: 0 B Textures: 42 / 1.4 MB Meshes: 12 / 194.6 KB Materials: 5 / 1.8 KB AnimationClips: 0 / 0 B AudioClips: 0 / 0 B Assets: 127 GameObjects in Scene: 2 Total Objects in Scene: 45 Total Object Count: 172
B – Interface of subtask	Draw Calls: 35 Tris: 1.0k Verts: 2.0k Batched Draw Calls: 0 Batched Tris: 0 Batched Verts: 0 Used Textures: 0 / 0 B RenderTextures: 0 / 0 B RenderTexture Switches: 0 Screen: 64x64 / 48.0 KB VRAM usage: 48.0 KB to 102.0 KB (of 256.0 MB) VBO Total: 15 - 54.0 KB VB Uploads: 0 - 0 B IB Uploads: 0 - 0 B Shadow Casters: 0 Visible Skinned Meshes: 0 Animations: 0	Total: 13.4 MB Delta: 0 B Textures: 71 / 17.4 MB Meshes: 15 / 108.3 KB Materials: 7 / 2.2 KB AnimationClips: 0 / 0 B AudioClips: 0 / 0 B Assets: 160 GameObjects in Scene: 2 Total Objects in Scene: 51 Total Object Count: 211
C – Instructions deployed	Draw Calls: 24 Tris: 7.0k Verts: 17.3k Batched Draw Calls: 0 Batched Tris: 0 Batched Verts: 0 Used Textures: 0 / 0 B RenderTextures: 0 / 0 B RenderTexture Switches: 0 Screen: 64x64 / 48.0 KB VRAM usage: 48.0 KB to 496.7 KB (of 256.0 MB) VBO Total: 18 - 448.7 KB VB Uploads: 0 - 0 B IB Uploads: 0 - 0 B Shadow Casters: 0 Visible Skinned Meshes: 0 Animations: 0	Total: 14.9 MB Delta: 0 B Textures: 71 / 17.4 MB Meshes: 18 / 1.6 MB Materials: 7 / 2.2 KB AnimationClips: 0 / 0 B AudioClips: 0 / 0 B Assets: 160 GameObjects in Scene: 2 Total Objects in Scene: 54 Total Object Count: 214
D – Interface for guide images	Draw Calls: 25 Tris: 476 Verts: 800 Batched Draw Calls: 0 Batched Tris: 0 Batched Verts: 0 Used Textures: 0 / 0 B RenderTextures: 0 / 0 B RenderTexture Switches: 0 Screen: 64x64 / 48.0 KB VRAM usage: 48.0 KB to 69.2 KB (of 256.0 MB) VBO Total: 10 - 21.2 KB VB Uploads: 0 - 0 B IB Uploads: 0 - 0 B Shadow Casters: 0 Visible Skinned Meshes: 0 Animations: 0	Total: 13.3 MB Delta: 0 B Textures: 71 / 17.4 MB Meshes: 10 / 42.6 KB Materials: 7 / 2.2 KB AnimationClips: 0 / 0 B AudioClips: 0 / 0 B Assets: 160 GameObjects in Scene: 2 Total Objects in Scene: 46 Total Object Count: 206
E – Connection between FIM and Installation/ Removal of components	Draw Calls: 43 Tris: 806 Verts: 1.3k Batched Draw Calls: 0 Batched Tris: 0 Batched Verts: 0 Used Textures: 0 / 0 B RenderTextures: 0 / 0 B RenderTexture Switches: 0 Screen: 64x64 / 48.0 KB VRAM usage: 48.0 KB to 83.4 KB (of 256.0 MB) VBO Total: 19 - 35.4 KB VB Uploads: 0 - 0 B IB Uploads: 0 - 0 B Shadow Casters: 0 Visible Skinned Meshes: 0 Animations: 0	Total: 13.3 MB Delta: 0 B Textures: 71 / 17.4 MB Meshes: 19 / 71.1 KB Materials: 7 / 2.2 KB AnimationClips: 0 / 0 B AudioClips: 0 / 0 B Assets: 160 GameObjects in Scene: 2 Total Objects in Scene: 55 Total Object Count: 215
F – Menu for the Installation or removal	Draw Calls: 14 Tris: 170 Verts: 228 Batched Draw Calls: 0 Batched Tris: 0 Batched Verts: 0 Used Textures: 0 / 0 B RenderTextures: 0 / 0 B RenderTexture Switches: 0 Screen: 64x64 / 48.0 KB VRAM usage: 48.0 KB to 52.0 KB (of 256.0 MB) VBO Total: 6 - 4.0 KB VB Uploads: 0 - 0 B IB Uploads: 0 - 0 B Shadow Casters: 0 Visible Skinned Meshes: 0 Animations: 0	Total: 13.3 MB Delta: 0 B Textures: 42 / 1.1 MB Meshes: 6 / 8.1 KB Materials: 6 / 2.0 KB AnimationClips: 0 / 0 B AudioClips: 0 / 0 B Assets: 128 GameObjects in Scene: 2 Total Objects in Scene: 39 Total Object Count: 167

G – Augmented Reality maintenance procedures	Draw Calls: 106 Tris: 95.8k Verts: 127.9k Batched Draw Calls: 0 Batched Tris: 0 Batched Verts: 0 Used Textures: 0 / 0 B RenderTextures: 0 / 0 B RenderTexture Switches: 0 Screen: 64x64 / 48.0 KB VRAM usage: 48.0 KB to 28.6 MB (of 256.0 MB) VBO Total: 412 - 28.5 MB VB Uploads: 0 - 0 B IB Uploads: 0 - 0 B Shadow Casters: 0 Visible Skinned Meshes: 0 Animations: 14	Total: 81.6 MB Delta: 0 B Textures: 414 / 24.1 MB Meshes: 412 / 57.1 MB Materials: 369 / 81.5 KB AnimationClips: 14 / 210.3 KB AudioClips: 0 / 0 B Assets: 1286 GameObjects in Scene: 436 Total Objects in Scene: 1761 Total Object Count: 3047
H - Use of software in real environment	Non applicable	Non applicable

Table 12 Android OS statistics of the different GUI developed for the software

In the side of rendering the number of draw calls plays a crucial role in the mobile software development, this number must be kept as low as possible, for this application the average number was 25.85 for the interfaces that only contain 2D information, like text, figures, tables, buttons; for the Augmented reality system a maximum of 106 draw calls was found, there is some discussion about what is an acceptable number of draw calls but it depends in the hardware, for this case a GALAXY tab 10.1 was tested with no problems found in performance. The number of vertices on the AR system was up to 127.9 K with no problem found. The VRAM usage is the approximate bounds of current video memory (VRAM) usage, for the system that only manage 2D information had a maximum for the range of 48 Kb – 496 Kb, but when the AR procedure is activated this variable had a maximum of 38 kb – 28.6 Megabyte, that could explain that in some step there was some slowness when changing the step, the 3D model are load dynamically in each task, for example in the removal of the High Stage Valve there are 15 models unload for the image target, then when the counter of current step starts moving, the system will load the correct model and unload any other 3D feature in the scene. In Figure 27 the jump in CPU usage and rendering is shown when the state of the tablet passes from only written instructions to AR with 3D model augmentations, later this level of processing will be reduce when the user come back to the 2D information.

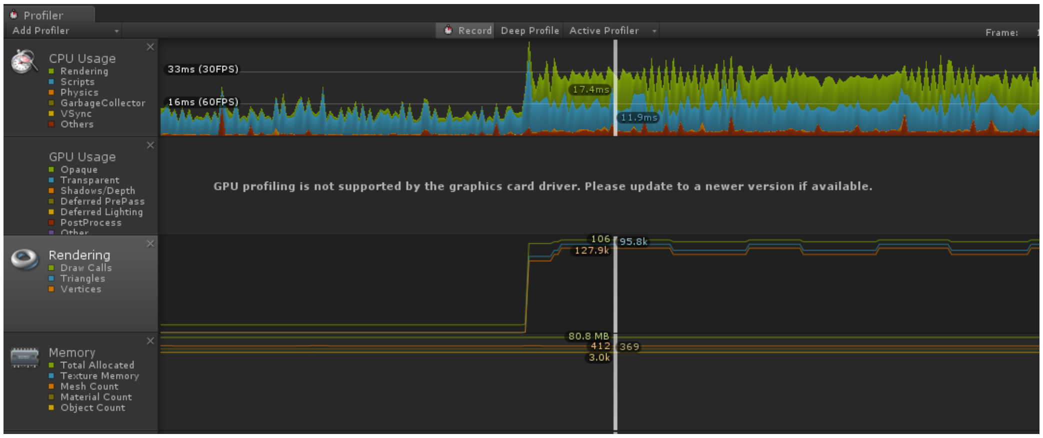


Figure 27 Changes in memory when the 3D model starts rendering

The CPU showed in average for the 2D information 13.7 Mb allocated in the RAM, for the Augmented Reality System a maximum of 81.6 MB was found due to the different activities of the CPU like tracking, rendering and changing information.

The total object in the scene for the 2D part was 197.5 contrasting with the 3047 objects in the HSV AR scene, this is because the 3D models were design with a lot of details in the geometry and for any geometry a texture was applied, then the animation works in somehow like copies of the same model with texture, a maximum size of 15 MB for the FBX exported model from 3Dsmax was allowed, this limit was impose after testing of different complex geometries to ensure stability in the compile software. The FBX file is later process by UNITY to produce the correct output to Android and iOS operating system.

Discussion

The timeframe for developing this project played an important role in the main findings of the software, as mentioned before, the iterative developing process had several milestones before the stable and complete version was ready for release, this milestones include both, the feedback for the airline and also the evaluation of the performance of the app when more documentation (Independent subsystems, 3Dmodels, 2D images, big quantities of text) was added.

To receive an insight in how much the AR subsystem for the installation and removal of components is expected to improve the performance of the task, an experiment was designed parallel to the developing of the app, this study was carefully proposed to be: representative of the assembly process in the aeronautical industry, introduce a high level of complexity to clearly identify the results, and independent of the gender of the person that was going to use the technology.

The experiment was an extension of the study that Mercado [39] did during his thesis dissertation; the main flaws reported on his experiment were corrected and the recommendations for the study were followed with some changes to get comparable results in the variables.

In the next section the results of the study will be presented, if the reader would like to get more information of the experiment please refer to **appendix A**. It is worth to note that the assembly was chosen because of its characteristics, it has two mirror symmetry axes where the user is likely to ignore the labels that indicate the correct position of each piece. It was ensured that there is only one correct solution to the assembly. As shown in chapter II there has not been studies of comparison of the AR technology and written instruction when the assembly has several parts that look alike and the correct solution depends on the instruction and the labels.

RV training project-1 was chosen to be the study case, this is a training project used to introduce prospective RV aircraft builders to the materials and techniques used in putting together an RV-10 airplane. The user assembled a short section of the flight control surface and, in the process, learned the basic skills needed during actual aircraft construction [40]. To reduce the time of sample and for safety issues the kit was properly prepared before the test, holes were drilled to size of rivets and the image targets of AR technology were positioned also every piece of the assembly was identify for the two sides: up/down faces. After the preparation, only the manual of assembly (AR or written), rivets and rivet-gun was necessary to finish. All operations could be performed with non-considerable physical effort, also all the labeled pieces belong to only one place to clearly identify when the user committed a mistake.

Two instructional procedures were prepared for the evaluation, one with written instructions similar to the sheets given to the user in the Aircraft procedures, the other was developed with Augmented Reality technology deploy with web cam and computer screen. According to the design of experiment theory the test has one factor (method of knowledge transference), 2 levels (Traditional Written Instructions and Augmented Reality Instructions) and 2 outputs (time for completing the assembly and quality).For the quality assessment a total of 46 points were assigned to the perfect assembly for the principal characteristics of the RV training kit, then the number of faults were summarize to see the effect of the process followed by the user.

N	Assembly Type	Average Assembly Time [Minutes]	Average Quality of Assembly
17	**TRADITIONAL**	50.16	76.60%
17	**AR**	41.52	94.63%

Table 13 Results of study: AR vs Traditional Written Instructions

The data gathered was ensure to be normal and ANOVA was done to conclude that the finding have a confidence interval of 99% necessary for the aeronautical industry, see **appendix A** for reference.

Table 13 summarize the results found in the experiment for the two methods of assembly for RV training kit, the time for assembly was 17.22% lower for the AR technique than the traditional written instructions also the quality of the assembly was seriously impact when using AR it reached a 94.63% compared to the 76.60% of the written instructions method, this represent a 24% increment in the quality with respect to the current methods in the company, this sample was composed by random male or female senior students of mechanical engineering with no previous knowledge of the task to ensure gathering of the learning curve while doing the test.

The experiment took into account the contributions made by the detailed written instructions for the assembly of mechanical components, where crucial specifications in the object must be made to ensure quality, in the airline case, to ensure the safety of the passengers and the integrity of the engine.

	AR technique	Written instruction	Conclusions
Alcazar et al, 2010	283.59	568.97	25% less time for of assembly in complex cases
Rios et al, 2012	41.52	50.16	17.2% less time for mirror symmetric complex assemblies

Table 14 Studies for time comparison of AR vs. written instructions performed at ITESM

With the information gathered in Table 14 and the recompilation of Table 4 it can be concluded that the AR system on mobile devices will improve the current procedures of maintenance of the CFM-56 engines, in Table 15 the work of the author Lerma is summarized, the usability of the AR markerless technology is given at approximately 80% with laptop computers [41], the used of tablets could increase the total usability of the system for markerless technology.

Total usability			
	P1: AR technique with markers (black and white)	P2: AR technique markerless (use of texturized images)	Conclusions
T1: Installation of components	72.02	69.52	The difference between both of the techniques was not big but according to the author the perceived effectiveness and satisfaction was higher for AR markerless technology
T2: Removal of component	84.45	80.33	
Total usability by technology	78.23	74.93	

Table 15 Usability study for markers and markerless AR techniques in the aeronautical area

It is expected that the mobile solution for the troubleshooting techniques and maintenance procedures will enhance the abilities of the users by not only taking the benefits of changing the current training methods in the company but also taking advantage of the mobility of the hardware with dual system with Augmented Reality & Virtual Reality, the touch capabilities of the state of the art tablets make the app friendly and easy to understand the great amount of information related to the isolation of faults, the formal evaluation and impact of the software presented in this project will be done in a second stage of development, the reader should take into account that most of the information is property of the company and it cannot be published.

Chapter 6 Conclusions and future work

A mobile solution to enhance the troubleshooting techniques and maintenance procedures of the Engine Air Bleed System of the BOEING 737 aircraft was proposed and developed in this investigation with the objective of improving the current processes of the Aeromexico Airline, the system can function on two aspects for training and for in situ operations, both of them use the same isolation system but for the installation and removal of engine components the system is able to run not only with Augmented Reality but also with Virtual Reality, this concept is commonly known as a Mixed Reality system [8]. The software can be compiled for Android (Galaxy tab, Motorola XOOM) & iOS (iPads, iPhones) operating systems to use the existent and new devices in the company.

Azuma et-al asked the following, given a system with ideal hardware and an intuitive interface, how can AR become an accepted part of a user's everyday life, just like a mobile phone or a personal digital assistant? Through films and television, many people are familiar with images of simulated AR. However, persuading a user to wear a system means addressing a big number of issues from fashion to security concerns [42]. In the research community almost no attention has been put in this subject, but now, that AR and mobile hardware technology are reaching matureness this problems must be study, for example Lerma concluded that the usability of the RA markerless technology was around 80% in the actual state [41], this could be an indicator that the state of the art of Augmented Reality is reaching a good performance point, where the next step is to produce applications with ergonomic hardware like the project presented in this work.

From the performance point of view the app developed in this investigation showed excellent results, the memory was dynamically manage to load and load assets in the system, all the information was approximately two touches in the screen of the screen. Figure 28 shows that all information processes must be at easy reach to effectively troubleshoot the EBAS, in this way the operator is only focusing in the task.

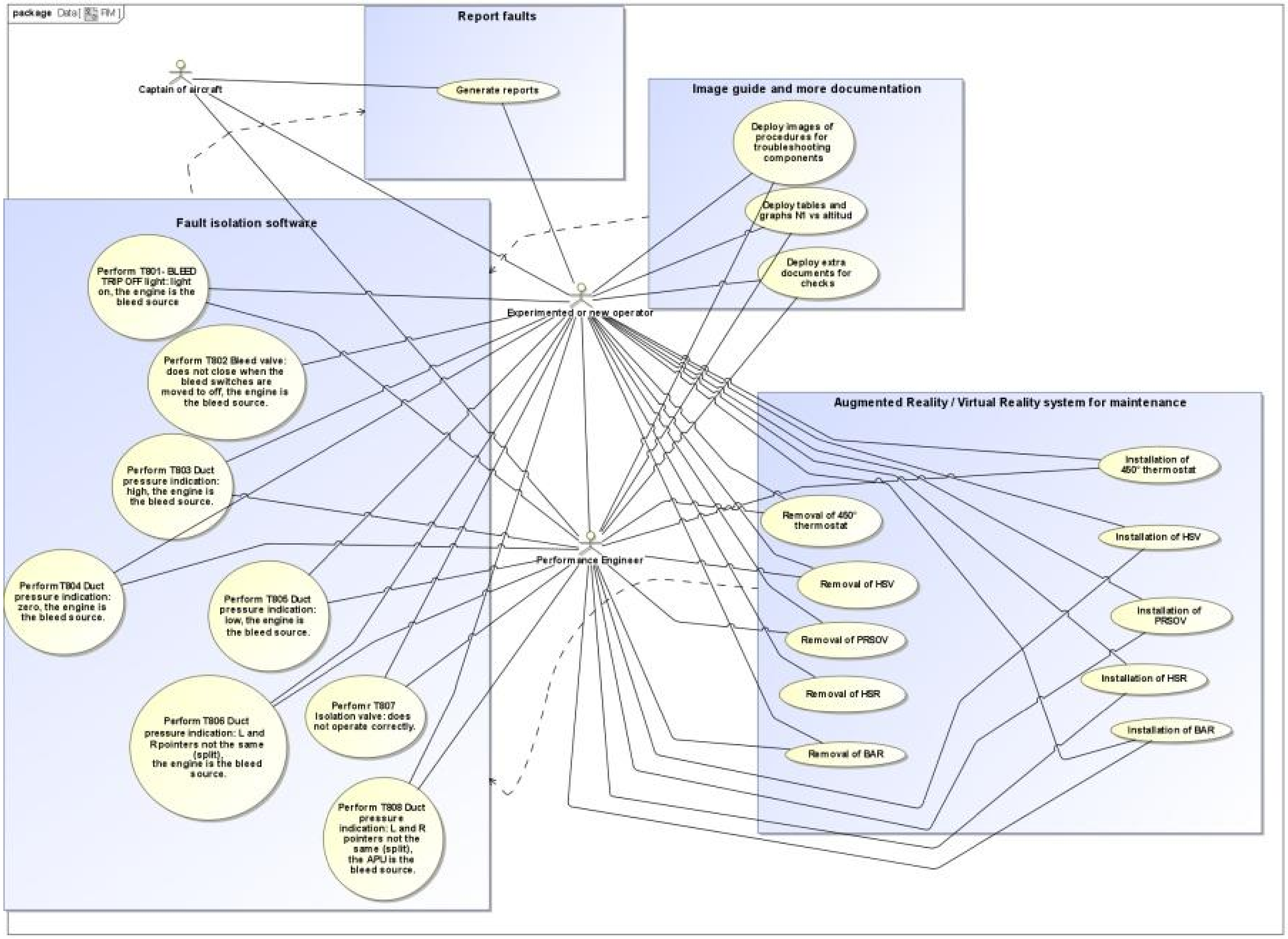


Figure 28 Use case diagram of fault isolation software

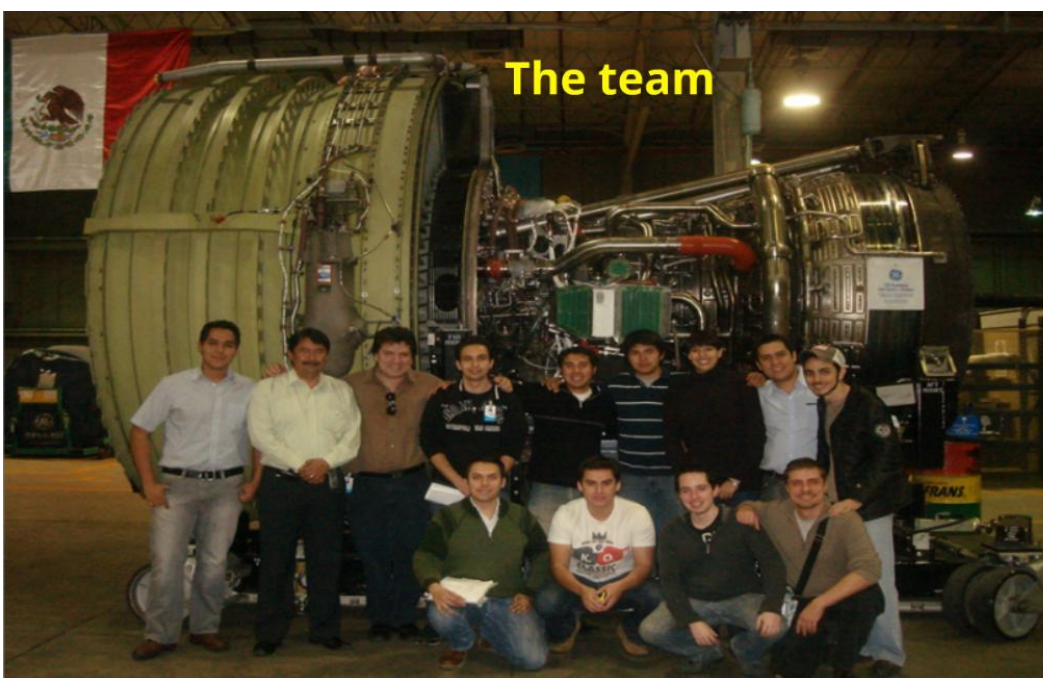
The final challenge to overcome is the acceptance of final users to take the system in the everyday environment, once the app is release in the hangar it will be of interest to study the resiliency of the engineers and operators (new & experienced) for using the technology; also the feedback from them will be of great importance to make the proper changes in the structure of the system.

Future work

- Introduce a system to recover data of the isolation task and maintenance to analyze how the mobile system helped in real conditions.
- Capture feedback of the operators after they use the app in real working conditions and perform if possible a statistical analysis to measure quantitatively the improvements in time or efficiency with respect to the current process.
- The current design of the software architecture allows the company to quickly develop more content for other subsystems, this is a window of opportunity to implement new processes in the same app, as shown in chapter II until now the evaluation of the software is satisfactory in terms of performance, the system could be expanded easily.

Publications and participation on international forums during the development of the project

- Innovation and Creativity Competition of the Motorola Design Center. Monterrey, México 2012.
- Third place award: Student manufacturing design competition presented at the 2012 Manufacturing Science and Engineering Conference of the ASME (University of Notre Dame, IN)
- An Introduction to Augmented Reality for Maintenance Operations. Conference ICTON 2011. Stockholm, Sweden.
- Factibilidad de la Tecnología de Realidad Aumentada en Mecánica Aplicada. Conference SOMIM 2011. Querétaro 2011.
- Augmented Reality: An Advantageous Option for Complex Training and Maintenance Operations in Aeronautic Related Processes. Conference HCI 2011. Florida, USA.



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Appendix A Report of experiment to measure improvement of the AR technique

In this section a more detailed description of the experiment performed to measure the changes for two different methods of assembly, the AR and the traditional written instructions, when the object has two mirror symmetry axes.

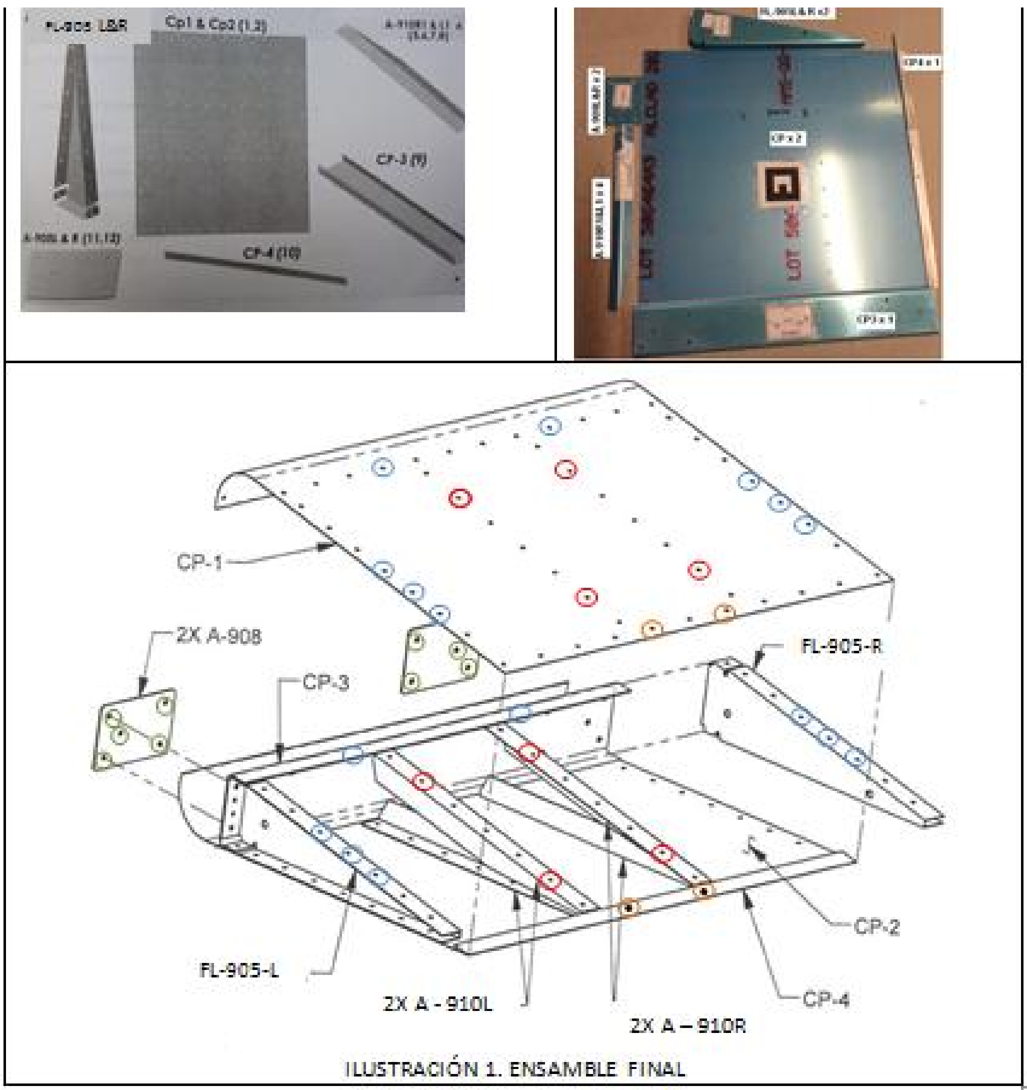

Figure 29 RV-10 training kit with assembly drilled holes in colors

Results of the study for the variable time and quality of the final assembly

Test Number	Assembly Type	Assembly Time [Minutes]	Quality of Assembly MAX 46 points posible
1	TRADITIONAL	51.2	44
2	TRADITIONAL	53.45	36
3	TRADITIONAL	56.06	45
4	TRADITIONAL	59.15	42
5	TRADITIONAL	45.19	32
6	TRADITIONAL	57.7166	38
7	TRADITIONAL	59.6166	43
8	TRADITIONAL	46.9	42
9	TRADITIONAL	41.2	35
10	TRADITIONAL	54.42	30
11	TRADITIONAL	37.55	36
12	TRADITIONAL	37.15	40
13	TRADITIONAL	50.88	17
14	TRADITIONAL	57.63	28
15	TRADITIONAL	41.15	25
16	TRADITIONAL	62.75	36
17	TRADITIONAL	40.76	30
1	AR	31.51	45
2	AR	54.03	43
3	AR	38.56	39
4	AR	58.15	46
5	AR	40.25	39
6	AR	38.69	44
7	AR	36.76	43
8	AR	46.83	43
9	AR	39.13	43
10	AR	36.82	44
11	AR	42.76	44
12	AR	42.01	43
13	AR	42.76	45
14	AR	21.95	45
15	AR	45.4	45
16	AR	46.4	46
17	AR	43.85	43

Inspection test of the final assembly for both methods:

Sub-assembly 1	Possible points
Correct position of A910 pieces	1
Correct riveting of A910 (4)	4
Sub-assembly 2	
Correct position of A910 pieces	1
Correct riveting of A910 (4)	4
Sub-assembly 3	
Correct orientation of A905	1
Correct orientation of A908	1
Correct riveting (10)	10
Sub-assembly 4	
Correct riveting of sub-assembly 1 (8)	8
Correct orientation of sub-assembly 1	1
Correct riveting of sub-assembly 2 (8)	8
Correct orientation of subassembly 2	1
Correct orientation of CP4	1
Correct riveting of CP4 (2)	2
General assembly	
Use of tooling	1
Correct use of rivet gun	1
Correct adjustment of pieces	2
Total	46

Results analysis of time variable

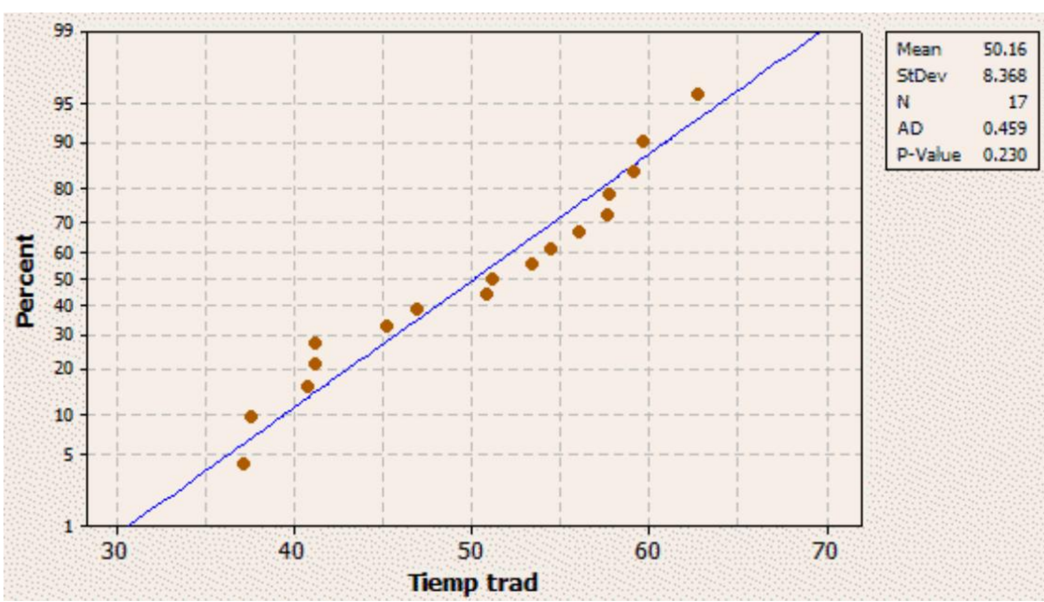

Figure 30 Normality test for variable time for written instructions method

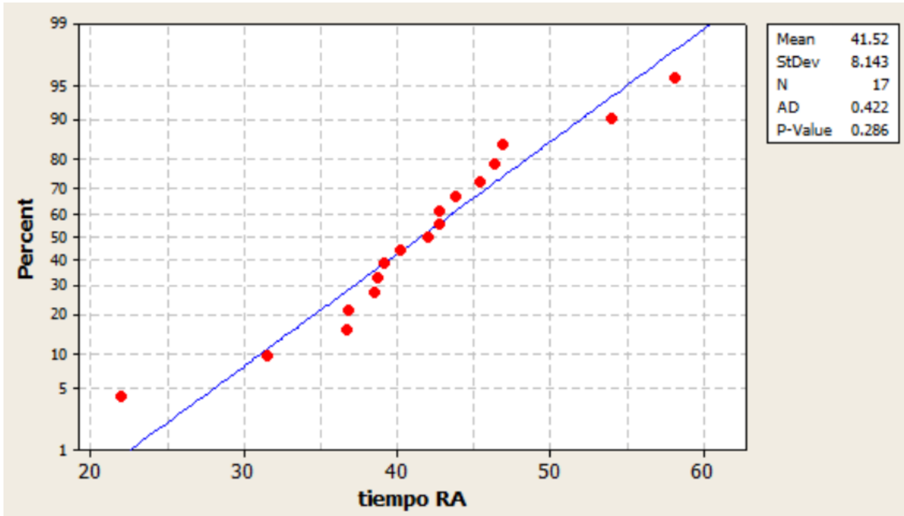

Figure 31 Normality test for variable time for RA method

Both sample data showed normal behavior, the next step was to perform an one way anova to corroborate that the sample are statistically different.

One way ANOVA: time vs method of assembly

```
Source  DF      SS     MS     F      P
Metodo   1   634.8  634.8  9.31  0.005
Error   32  2181.4   68.2
Total   33  2816.2

S = 8.256   R-Sq = 22.54%   R-Sq(adj) = 20.12%


                          Individual 99% CIs For Mean Based on
                          Pooled StDev
Level   N    Mean  StDev  --------+---------+---------+---------+-
1      17  50.163  8.368                   (----------*----------)
2      17  41.521  8.143  (----------*----------)
                          --------+---------+---------+---------+-
                               40.0      45.0      50.0      55.0

Pooled StDev = 8.256


Grouping Information Using Fisher Method

Metodo   N    Mean  Grouping
1       17  50.163  A
2       17  41.521    B

Means that do not share a letter are significantly different.
```

The p-value is less than 0.05, it can be concluded that the samples are different.

Fisher average computation

```
Fisher 99% Individual Confidence Intervals
All Pairwise Comparisons among Levels of Metodo

Simultaneous confidence level = 99.00%


Metodo = 1 subtracted from:

Metodo    Lower   Center   Upper   ---+---------+---------+---------+------
2       -16.397   -8.642  -0.887   (----------*----------)
                                   ---+---------+---------+---------+------
                                   -14.0     -7.0       0.0       7.0
```

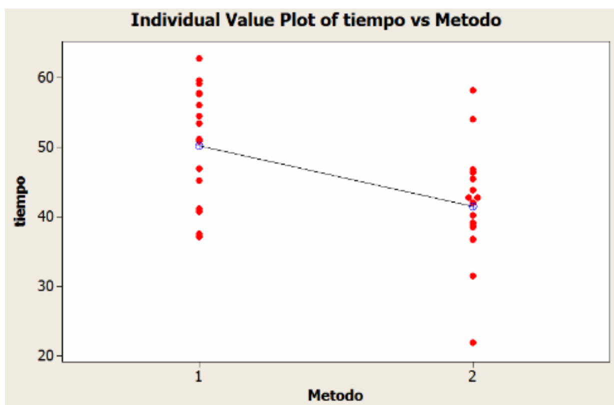

Figure 32 Individual plot of time vs. method of assembly. Written instructions:1 & RA manual:2

Figure 32 show graphically the results of the time variable, it is concluded that the AR method can reduce time in the maintenance and assembly domain.

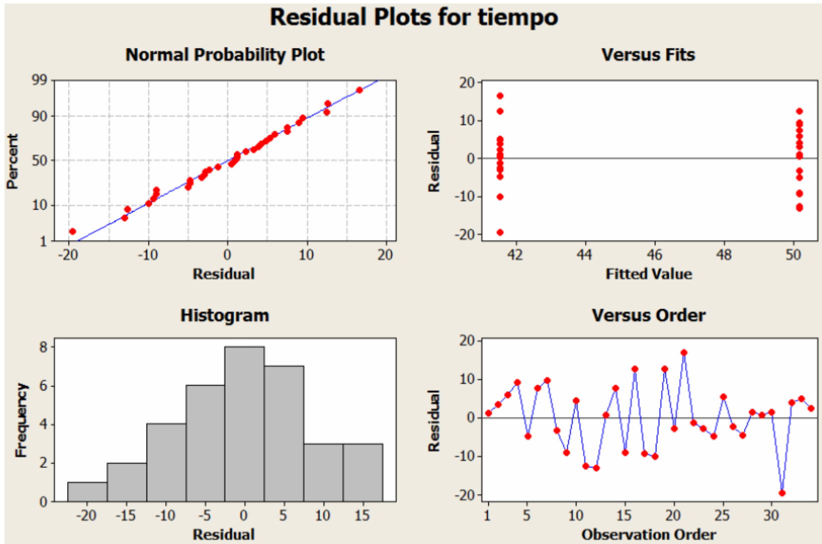

Figure 33 Residuals plot for time

Result of quality evaluation of the assembly

In the same way a normality test and ANOVA was done to the sample data of quality.

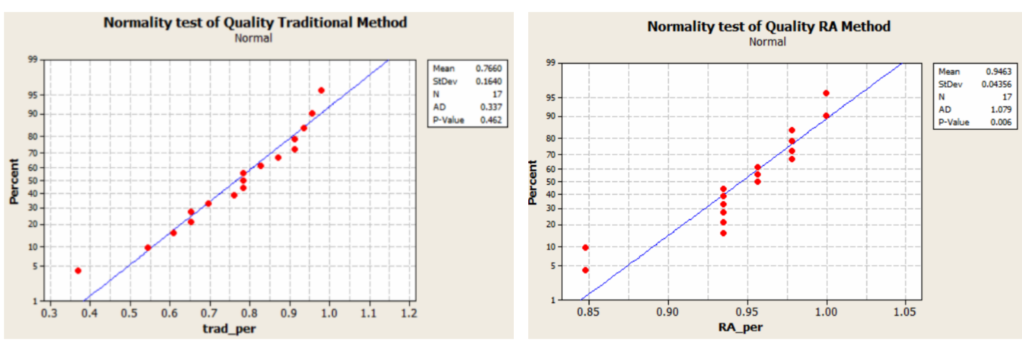

Figure 34 Normality test for quality with written instruction manual and AR method

The data for quality shown non normal behavior but there are statistical tests to compare two independent groups that do not require **large normally** distributed samples like the Mann-whitney test.

The adjusted p-values are interpreted the same as the other p-values: If the p-value is less than alpha, then reject the null hypothesis; if the p-value is greater than alpha, fail to reject the null hypothesis.
The null hypothesis is that both medians are equal. The alternative hypothesis is set by the user in the main dialog box of the Mann Whitney test with 99% of confidence interval.

Mann-Whitney Test and CI: trad_per, RA_per

```
           N  Median
trad_per  17  0.7826
RA_per    17  0.9565


Point estimate for ETA1-ETA2 is -0.1522
99.0 Percent CI for ETA1-ETA2 is (-0.2826,-0.0434)
W = 186.5
Test of ETA1 = ETA2 vs ETA1 < ETA2 is significant at 0.0001
The test is significant at 0.0001 (adjusted for ties)
```

From the Mann-Whitney test can be concluded that the samples are different and the median of the RA method for quality is bigger than the written instructions method.