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Automating Contextualized Maintenance Documentation

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Abstract. Currently, task support information in aircraft maintenance is mostly provided using paper-based solutions, which are burdensome, slow and prone to error. Aircraft maintenance documentation contains vast amounts of information irrelevant for the task at hand and even for the simplest tasks multiple documents need to be consulted. Next to these issues with the documentation itself, Aircraft Maintenance Technicians (AMTs) have very limited on-site access to support information. These factors lead to 15-20% of hands-on-aircraft time being wasted on acquiring the right information or not using maintenance documentation for task support at all, risking maintenance error. This paper describes the development of a system for a first level of contextualization of maintenance documentation to simplify the retrieval of task support information. Combining a tailor-made ontology with a relational database system for Ontology-Based Data Access (OBDA), maintenance documents relevant to a specific aircraft registration mark can be identified. The system contributes to the research field of knowledge management by using OBDA for selecting relevant maintenance documents stored in a regular file folder. Future work will focus on increasing the level of contextualization, development of a mobile tool for on-site access and prototype verification and validation in an operational environment.

Keywords. Aircraft maintenance, maintenance efficiency, contextualized documentation, ontology-based data access, human factors, mobile tools

Introduction

Air transport is well-known for being a very safe and reliable method of transportation. The high level of safety in air transport is achieved while Revenue Passenger-Kilometers (RPKs) have continuously been increasing over the last decade; a trend which is expected to continue at an average rate of approximately 6% a year [1]. One of the most important factors contributing to safety is maintenance, which is based on strict schedules that originated during the development of the Boeing 747. This eventually led to the MSG-3 maintenance approach, now used for all commercial aircraft [2].

A growing market creates challenges from the maintenance perspective. It leads to more required maintenance work, but currently the maintenance workforce is declining [3]. Meanwhile, AMTs require more knowledge to adequately perform maintenance on increasingly complex systems. Acquiring task-specific information is time consuming because aircraft maintenance documentation is notoriously extensive, containing vast amounts of information not directly relevant to execute a task [4], and the information has to be collected from multiple sources. AMTs also have very limited access to task support information; maintenance documentation is usually accessed through workstations (i.e. desktop computers), which are not available in the direct vicinity of the AMT's workplace. This is especially problematic for line AMTs, as the distance from the platform to a workstation can be significant [5]. These issues combined lead to 15-20% of hands-on-aircraft time being wasted on acquiring the right information [6] and negatively affects the operational performance of airline operators by increased turnaround times (TAT) and maintenance errors [7] that lead to increased maintenance costs [8], flight schedule disruptions, major malfunctions [9] and in some cases accidents.

As part of the European Union's Clean Sky 2 research programme, the Airline Maintenance Operations implementation of an E2E Maintenance Service Architecture and its enablers (AIRMES) project aims to develop multiple Integrated Mobile Tools to support the AMT during maintenance tasks. These tools aim to improve maintenance execution efficiency, reduce turnaround times and can lead to cost reductions that are estimated at 195 to 395 M€ annually [10]. Within the scope of AIRMES, a mobile tool for contextualized documentation will be developed to address the weaknesses of maintenance documentation. This paper describes the development of a database system to provide initial contextualization of maintenance documents. Ontology-Based Data Access (OBDA) is implemented to query various types of maintenance documents and is based on a relational database system, a tailor-made ontology and an integrated software platform to query the database. Using the aircraft's registration mark as input, the database system returns the relevant maintenance documents, based on contextual information derived from the registration mark (e.g. aircraft manufacturer, family). Qualitative and quantitative assessment of the database system show very accurate results in retrieving relevant maintenance documents with excellent performance. In the remainder of the paper, human factors in aircraft maintenance are discussed first, followed by the development of the database system and a discussion of the results obtained. Finally, conclusions are drawn and future research is identified.

1. Human factors in aircraft maintenance

To understand how AMTs currently use maintenance documentation, knowledge of the human factors involved is essential. Human error has been defined in different ways, but all share the idea that, for one, humans are organic mechanisms with failure rates and tolerances similar to hardware and software elements of a system, and secondly, human error is a negative term for normal human behavior in less than ideal environments [11]. Several models were developed to find causes for human error in aviation maintenance and the most well-known model for human factors that lead to error was developed by Gordon Dupont in 1993, known as the “Dirty Dozen” [12].

In 2008, Hobbs investigated the conditions in which AMTs work and identified resulting physical (e.g. omissions) and psychological actions (e.g. wrong assumptions) that lead to error [13]. AMTs are confronted with exceptional circumstances; adverse weather, physical and spatial challenges and the unique sense of stress because the work performed can influence the safety of future flights. Line maintenance is performed within the flight schedule and creates an increased sense of pressure on the

AMT to fulfill maintenance tasks on time to avoid flight disruptions. Time pressure typically increases the chance of individual errors as result of memory lapses and procedural violations. Poor maintenance procedures and documentation can also lead to errors. The FAA found that AMTs spend 25-40% of their time dealing with maintenance documentation, including administrative work [13; 14]. Procedures and manuals are often impractical to use; prescribed procedures are not in agreement with the way an AMT performs a task and manuals are written with extensive use of warnings, complicating extraction of useful information. Access to maintenance documentation is also limited, especially for line AMTs working on the platform: depending on the layout of the airport this can take up to half an hour [5]. The issues with maintenance documentation result in a continuous trade-off being made by AMTs when they need to consult task-specific information [15]. A study showed that the AMT will only look for the required information if the benefit or value of that information exceeds the cost (e.g. time, effort) to acquire it. The AMT individually determines the added value of the documentation based on experience (risking complacency), but also based on previous experience with maintenance documentation [16]. These findings, together with the strong relation between aviation maintenance errors and the content and (non-)use of maintenance documentation [7; 9], show the importance of using correct, complete and relevant maintenance documentation during task execution.

2. Development of a proof of concept for contextualized documentation

To address the weaknesses of maintenance documentation and its implications, this work introduces a proof of concept to contextualize maintenance documentation. The developed system includes a tailor-made ontology, a relational database system containing maintenance documentation and the fleet information, as well as a software solution to integrate the ontology for Ontology-Based Data Access (OBDA).

2.1 Ontology development

The database system uses a concept developed in previous work by Lattner and Apitz [17], which uses metadata captured in ontologies to contextualize information. The use of an ontology to structure and classify information in a database system has several benefits [18], including: sharing a common understanding of the structure of information, enabling reuse of domain knowledge, making domain assumptions explicit (i.e. assumptions can easily be changed when knowledge about the domain changes) and separating domain knowledge from operational knowledge. Especially in an innovative industry like aviation, where new knowledge continuously becomes available, the benefit of using an ontology to describe the domain is evident. To be able to establish relations between the registration marks in a fleet and the maintenance documents related to it, an ontology representing the aircraft models in the fleet is required. With no ontology readily available, an ontology was developed based on the fleet of KLM Royal Dutch Airlines using Stanford's open-source ontology editor Protégé. Table 1 shows a sample of KLM's fleet information, with the registration mark (Reg) and aircraft type (Aircraft Type) as relevant information for the ontology.

Table 1. A sample of KLM's fleet information.

Reg	Aircraft Type	Aircraft Name	Age
PH-AKA	Airbus A330-303	Times Square - New York	3.5 Years
PH-AKB	Airbus A330-303	Piazza Navona - Roma	3.5 Years
PH-BGN	Boeing 737-7K2 NG	Jan van Gent / Gannet	4.4 Years
PH-BGO	Boeing 737-7K2 NG	Paradijsvogel / Bird of Paradise	4.4 Years

Following from the registration mark the aircraft type can be determined and contextual information can be extracted. For example, registration mark PH-AKA has manufacturer Airbus and belongs to the A330 family. Figure 1 shows the part of the ontology for registration mark PH-AKA, showing the relations between aircraft type "Airbus A330-303" and its related classes: "Airbus" (hasManufacturer), "A330" (hasFamily). Other classes defined in the ontology were discarded for the proof of concept, because relations could not be established consistently (e.g. engine models and aircraft version) or including the information would lead to unreliable results (aircraft series, discussed in section 3.1). The ontology also includes relationships not shown in Figure 1, for example disjoints between manufacturers (e.g. Boeing is disjoint with Airbus) and disjoints between aircraft families (e.g. A330 is disjoint with A350 and A380). One of the benefits of a properly defined ontology is that new classes or individuals can automatically be classified by a reasoner through inference and thereby inherit all the properties of the class it is assigned to.

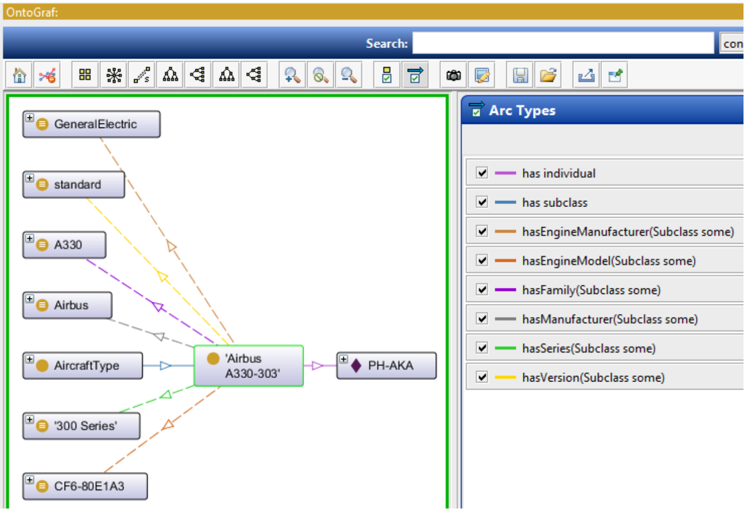

Figure 1. Graphical representation of the aircraft type ontology in Protégé.

2.2 Database development

With the ontology available, a database for the maintenance documents was set up. Because most maintenance documents are available in the Portable Document Format (PDF), the goal was to use a system that can directly use this file format. Database systems can work with Binary Large Objects (BLOBS) like PDF files in two ways: store them directly in the database, which can cause performance issues with larger files [19], or store them in a separate file system. A separate file system provides good performance, also for larger files such as Aircraft Maintenance Manuals (AMMs), but generally lacks the integration of essential functionality for the task at hand, namely full-text search. Currently, the only solution available to work with a separate file system and have full-text search functionality is provided by the FileTable feature in Microsoft's SQL Server (2012 and later). The FileTable feature can access and search within maintenance documents, stored in a regular (network) file folder, in their unstructured, original file format. Hence, a Microsoft (MS) SQL Server with the FileTable feature enabled was set up with access to a set of maintenance documents in a network file folder.

Next to the maintenance documents, a table with the fleet information was imported into the database in order to link registration marks from the fleet to aircraft type classes in the ontology. The registration marks could be included in the ontology directly, but this is deliberately avoided to keep the ontology independent from the airline the system is used for. This way, the ontology can be used for any fleet that is imported into the database, provided all the aircraft types in the fleet are described in the ontology. Using a script, distinct columns for the aircraft manufacturer, family and series were automatically added to the fleet information table to be able to establish links with the corresponding classes in the ontology. The resulting SQL database table is shown in Figure 2.

	reg	AircraftType	AircraftName	Age	Manufacturer	Family	Series	Model
1	PH-AKA	Airbus A330-303	Times Square - New York	3.5 Years	Airbus	A330	300	Airbus A330-300
2	PH-AKB	Airbus A330-303	Piazza Navona - Roma	3.5 Years	Airbus	A330	300	Airbus A330-300
3	PH-AKD	Airbus A330-303	Plaza de la Cathedral - Habana	3.4 Years	Airbus	A330	300	Airbus A330-300
4	PH-AKE	Airbus A330-303	Praça de Rossio - Lisboa	2.6 Years	Airbus	A330	300	Airbus A330-300
5	PH-AKF	Airbus A330-303	Hofplein - Rotterdam	0.8 Years	Airbus	A330	300	Airbus A330-300

Figure 2. Sample of the modified KLM fleet information in the database.

With separate columns for the manufacturer, family and series information, links with the related classes in the ontology can be made by using so-called mappings.

2.3 Linking the ontology to the database for OBDA

Multiple methods for mapping of ontologies onto relational databases are available, all having specific benefits and drawbacks. A recent survey of state-of-the-art methods for automatic and lossless mapping of ontologies onto relational databases has shown that the several available methods still have issues with loss of structure, loss of information or are not fully automatic [20]. A new, promising method is provided by Ontop, developed at the Free University of Bozen-Bolzano in Italy. Although the method does not support automatic mappings, it proves to be one of the best approaches for OBDA. Unlike other methods, which have the ontology as a virtual layer between the source database and the query engine, Ontop provides direct access to the sources, the ontology and the mappings (Figure 3), avoiding loss of metadata and performance or memory issues the other approaches have. Ontop is provided as a plugin for Protégé and consists of a tool for creating mappings as well as a reasoner and query engine, enabling on-the-fly querying of the underlying database using the SPARQL query language [21]. Quest has superior SPARQL-to-SQL translations compared to other systems and outperforms any other known methods for OBDA, such as Virtuoso RDF Views and D2RQ [22].

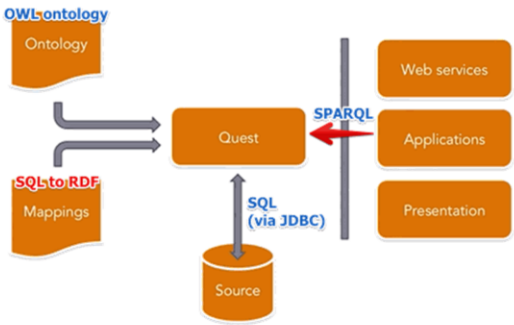

Figure 3. The Ontop framework.

Using Ontop and its plugin for Protégé, a total of 35 mappings were created. A mapping consists of a mapping identifier, a target and a source. The source refers to specific information in a database table, the target states a set of RDF triples and the mapping identifier is simply used to name the mapping. RDF triples state relationships between resources and always consist of a subject, a predicate and an object.

```
Manufacturer-Airbus
  :{Manufacturer}/{Reg} a :Airbus ; :hasModel {Model} ; :hasManufacturer {Manufacturer} ; :hasFamily {Family} ;
  :hasSeries {Series} ; :namedType {AircraftType} ; :name {AircraftName} ; :age {Age} .
  SELECT * FROM FleetInfoKLM WHERE Manufacturer = 'Airbus'
```

Figure 4. Manufacturer mapping for Airbus.

Figure 4 shows an example of a mapping to link registration marks in the database table having manufacturer Airbus to the class Airbus in the ontology. Similarly, mappings were made to link all relevant columns in the database table to classes in the ontology. The final mappings establish a link between a distinct aircraft model, 9 in the case of KLM, and its related maintenance documents. An example of such a mapping is shown in Figure 5. The target relates the subject, a registration mark, to an aircraft class and its related documents. Relevant documents are identified in the source of the mapping, where information from the fleet information database table is joined with information in the maintenance document FileTable, under the condition that specific keywords are found in the document (i.e. defined in the WHERE statement).

```
A330-303-Docs
  :{Model}/{Manufacturer}/{Family}/{Series}/{Reg} a :A330-303 ; :docName {name} .
  SELECT FleetInfoKLM.Reg, FleetInfoKLM.Model, FleetInfoKLM.Manufacturer, FleetInfoKLM.Family, FleetInfoKLM.Series,
  MaintenanceDocumentation.name, MaintenanceDocumentation.path_locator FROM MaintenanceDocumentation
  JOIN FleetInfoKLM
  ON FleetInfoKLM.Manufacturer ='Airbus' AND FleetInfoKLM.Family ='A330' AND FleetInfoKLM.Series ='300'
  WHERE (CONTAINS(file_stream,'Airbus') AND CONTAINS(file_stream,'A330'));
```

Figure 5. Mapping to relate the aircraft model A330-303 to its related documents.

With all required mappings available, relevant maintenance documents in the database can be identified by entering a registration mark in the SPARQL query engine. From the registration mark contextual information about the manufacturer, family and series is obtained to full-text search maintenance documents for the associated keywords with the FileTable feature. When the keywords are identified in a maintenance document, the document is returned as relevant. The result of a query for registration mark "PH-AKA" is shown in Figure 6.

Registration	Name	Model
:Airbus%20A330-300/Airbus/A330/300/PH-AKA	"EASA_AD_2014-0148_1.pdf"	<Airbus A330-300>
:Airbus%20A330-300/Airbus/A330/300/PH-AKA	"EASA_AD_2014-0248_1.pdf"	<Airbus A330-300>

Figure 6. Result for relevant maintenance documents for PH-AKA.

3. System results

The developed database system was assessed with regard to quality and performance, using freely available Airworthiness Directives (ADs). For each of the distinct aircraft families in the KLM fleet, being Boeing 737/747/777/787 and the Airbus A330, 2 ADs are added to the database per batch, after which the respective tests are performed.

3.1 Qualitative assessment

To test if the system returns the correct relevant maintenance documents, a qualitative assessment was performed over the first batch of 10 ADs. For this, results of the full-text search function of the FileTable were compared with a manual search through the documents to verify that the keywords for manufacturer, family and series information of an aircraft registration mark are correctly identified in the documents. The qualitative assessment showed that inclusion of the series information leads to unreliable results. This is caused by two factors. Firstly, the command used by the FileTable feature searches documents for exact keyword matches; when an AD refers to "*Airbus A330-201*", the FileTable keyword search will not find a match with the Airbus 200 series. This is beneficial to avoid false positives based on other information containing the x00 format, such as the year 2006, but prevents the system to identify documents relevant to a specific aircraft series. Secondly, the series information is not always stated in the AD. Documents may refer to "*all series*" of a family, and thus an exact match for a specific aircraft series cannot be found. More advanced methods for the full-text search implementation may be developed to overcome these issues, but are not included in this initial proof of concept. Hence, the aircraft series information was omitted in further assessments.

3.2 Performance assessment

The assessment was continued with a focus on the performance by determining the impact on query runtime when the number of available maintenance documents in the database is gradually increased by batches of 10 ADs. Starting with a batch of 10 documents, one registration mark for each of the 9 distinct aircraft models in KLM's fleet is used as input to query the database for relevant maintenance documents. The performance is measured by the query runtime, defined as the time from initiating the query until displaying the result. This is repeated five times per batch for every registration mark, leading to a total of 45 measurements per batch.

Query runtimes were measured for a method with and without OBDA integration (referred to as OBDA and SQL, respectively) to be able to assess the effect of using an ontology on query runtime. Querying the database without OBDA implementation is possible because the current database structure is still relatively simple. Once the complexity increases, for example when engine model information is added, the benefits of OBDA (i.e. having a high-level, easily adaptable structure independent from the database structure) become more evident. The results are plotted in Figure 7, with on the horizontal axis the batch number and on the vertical axis the average query runtime of 45 measurements per method. It shows that the OBDA method initially has lower performance than the SQL method, but from batch 2 onwards consistently outperforms the SQL method by approximately a factor 2.

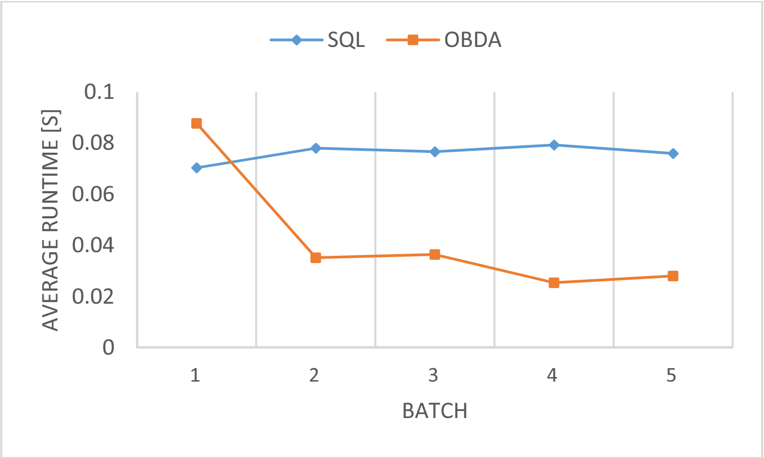

Figure 7. Average query runtime per batch for SQL and OBDA.

The results are remarkable considering that the developers of Ontop confirmed that table joins in the source of the mappings, as well as the CONTAINS statement used for the full-text search in the FileTable feature, are not fully supported. Moreover, the OBDA method requires extra processing to link the database with the ontology through mappings. Further tests showed similar behavior and more research is required to determine the cause.

4. Conclusions

A database system was developed to retrieve relevant maintenance documents, using the aircraft registration mark as input. The core of the database system is Microsoft SQL Server and the maintenance documentation stored in a FileTable with full-text search functionality. An approach for OBDA was pursued to benefit from the high-level conceptual schema, relations and domain knowledge of an ontology. To implement OBDA, an ontology for the domain of commercial aircraft was developed and integrated using the Ontop plugin for Protégé. Qualitative and quantitative assessments showed that fast and reliable results can be obtained when the series information is discarded. After initialization, the OBDA approach retrieves relevant maintenance documents approximately twice as fast as SQL.

The OBDA method contributes to the research field of knowledge management by providing OBDA for unstructured data, such as maintenance documents in PDF, by using the FileTable feature of Microsoft SQL Server in combination with Ontop for ontology integration. While the level of contextualization of the database system is limited, it provides a functional proof of concept for contextualizing maintenance documentation. The methodology can be applied to other domains by substituting the ontology and alter the mappings accordingly.

Current disadvantages of the developed system are the dependency on Microsoft's FileTable feature, including its incompatibilities with Ontop, and lack of support for automated mappings. These disadvantages will be addressed in future work, which will also focus on increased levels of contextualization, development of a mobile tool for on-site access and prototype verification and validation in an operational environment to assess potential time and cost savings. Such a system does not only tackle the limited accessibility for line maintenance technicians, but also improves the usability of maintenance documentation, and could significantly reduce the time currently wasted on acquiring task-specific information. The likelihood of both flight schedule disruptions and maintenance errors will be reduced, thereby increasing the operational efficiency and overall safety of air transport.

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