Proxim-CBR: A Scaleable Grid Service Network for Mobile Decision Support

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Abstract. With the emergence of Grid computing and service-oriented architectures, computing is becoming less confined to traditional computing platforms. Grid technology promises access to vast computing power and large data resources across geographically dispersed areas. This capability can be significantly enhanced by establishing support for small, mobile wireless devices to deliver Grid-enabled applications under demanding circumstances. Grid access from mobile devices is a promising area where users in remote environments can benefit from the compute and data resources usually unavailable while working out in the field. This is reflected in the aircraft maintenance scenario where decisions are increasingly pro-active in nature, requiring decision-makers to have up-to-date information and tools in order to avoid impending failures and reduce aircraft downtime. In this paper, an application recently developed for advanced aircraft health monitoring and diagnostics is presented. CBR technology for decision support is implemented in a distributed, scaleable manner on the Grid that can deliver increased value to remote users on mobile devices via secure web services.

1 Introduction

This paper describes a distributed, service-oriented Case-Based Reasoning (CBR) system built to provide knowledge-based decision support in order to improve the maintenance of Rolls-Royce gas turbine engines [1]. Figure 1 shows a typical gas turbine engine (GTE) used to power modern aircraft. As of 2006 there are around 54,000 of these engines in service, with around 10M flying hours per month. These GTEs, also known as aero engines, are extremely reliable machines and operational failures are rare. However, currently great effort is being put into reducing the number of in-flight engine shutdowns, aborted take-offs and flight delays through the use of advanced health monitoring technology. In this maintenance environment, decisions are increasingly pro-active in nature, requiring decision-makers to have up-to-date information and tools in order to avoid impending failures and reduce aircraft downtime. This represents a benefit to society through reduced delays, reduced anxiety and reduced cost of ownership of aircraft.

Figure 1. A Rolls-Royce Gas Turbine Engine

Grid computing [2] from mobile devices is a promising area where users in remote environments can benefit from the compute and data resources usually unavailable while working out in the field. This paper describes how Grid, CBR and mobile technologies are brought together to deliver a *substantial* further improvement in maintenance ability by facilitating the wide-scale communication of information, knowledge and advice between individual aircraft, airline repair and overhaul bases, world-wide data warehouses and the engine manufacturer. This paper focuses on *Proxim-CBR*, a recently developed system, as an example of how Grid technology can be extended to handheld devices to support pro-active mobile computing in a dynamic aircraft maintenance environment.

2 Related Work

The *Rolls-Royce University Technology Centre* (UTC) *in Control and Systems Engineering* at The University of Sheffield has a long history of using CBR for engine health monitoring and diagnostics. The UTC has actively explored a variety of on-wing control system diagnostic techniques and also portable maintenance aid applications. CBR techniques were applied in developing a portable PC-based Flightline Maintenance Advisor [3, 4] to correlate and integrate fault indicators from the engine monitoring systems, Built-In Test Equipment (BITE) reports, maintenance data and dialog with maintenance personnel to allow troubleshooting of faults (figure 2). The primary advantage of the CBR-based tool over a traditional paper-based Fault Isolation Manual is its capability to use knowledge of the pattern of multiple fault symptoms to isolate complex faults. This effort was eventually escalated to the development of an improved Portable Maintenance Aid for the Boeing 777 aircraft. The outcome of these initiatives included the implementation of a portable Flightline Maintenance Advisor that was trialled with Singapore Airlines.

More recently, rather than using a portable computer which needs updating with new data as it becomes available, it was clearly desirable for a CBR system to be accessed remotely by engineers over a computer network. The advantage of this is that it is easier to support and it also allows search of an extensive knowledge base of historical maintenance incidents across an entire fleet of engines. This was evident in the outcome of a large-scale initiative that explored this potential and developed new solutions [5, 6]. The *Distributed Aircraft Maintenance Environment* (DAME) project was a pilot project supported under the United Kingdom e-Science research programme in Grid technologies. DAME was particularly focused on the notion of proof-of-concept, using the Globus Toolkit and other emerging Grid technologies to develop a demonstration system. This was known as the DAME Diagnostic and Prognostic Workbench that was deployed as a Web-enabled service, linking together global members of the DAME Virtual Organisation and providing an Internet-accessible portal to very large, distributed engine data resources, advanced engine diagnostic applications and supercomputer clusters that delivered the required processing power. DAME tackled complex issues such as security and management of distributed and non-homogenous data repositories within a diagnostic analysis framework with distributed users and computing resources.

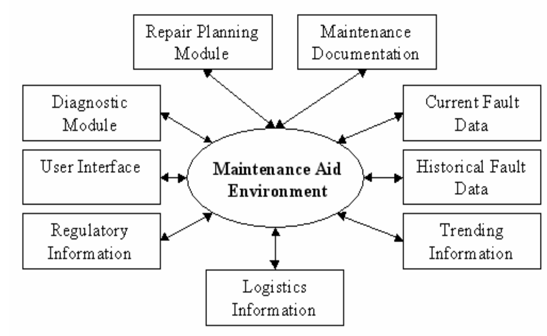

Figure 2. Structure of the Flightline Maintenance Advisor

Current research includes work being done in the *Business Resource Optimisation for Aftermarket and Design on Engineering Networks* (BROADEN) project. BROADEN is a UK DTI funded project [7], led by Rolls-Royce Plc, that aims to build an internal Grid at Rolls-Royce to further prove, in a production environment, the technologies developed in DAME. This will include integrated diagnostic and prognostic tools for health monitoring across development test, production pass-off and in-service aero engines, and the formulation of a strategy to transfer proven Grid technology to production networks. This project supports the "Health Management and Prognostics of Complex Systems" research theme from the Aerospace Innovation and Growth Team's National Aerospace Technology.

3 Engine Diagnostics and Maintenance

A fundamental change of emphasis is taking place within companies such as Rolls-Royce Plc where instead of selling engines to customers, there is a shift to adoption of power-by-the-hour contracts. In these contracts, the engines are effectively leased to clients and the engine manufacturer retains responsibility for maintaining the engine. To support this new approach, improvements in in-flight monitoring of engines are being introduced with the collection of much more detailed data on the operation of the engine. New engine monitoring equipment [8] can record up to 1GB of data per engine for each flight. In the future, Terabytes of data could be transmitted every day for diagnostic and prognostic purposes.

3.2 The Data Capture Process

The Engine Control Unit (ECU), also known as a Full Authority Digital Engine Controller (FADEC), has a test port to which the Engine Management System (EMS) connects to access data. The ECU test point can provide many data parameters. Other systems can interface with the EMS and gain access to any of the data provided by the ECU. The Engine Monitoring Unit (EMU), as fitted to newer engines, includes sophisticated built-in vibration monitoring functionality and specialized vibration feature detectors. A Digital Flight Data Recorder (DFDR) records the aircraft airframe and engine parameters and can be downloaded after every flight. At present, snapshots of key engine performance data at automatic intervals are sent to ground-based systems via the Aircraft Communications Addressing and Reporting System (ACARS), along with routine data such as departure reports, arrival reports, passenger loads, fuel data, and much more. This data is transmitted by VHF radio link and satellite. However, the costly pay-per-kilobit ACARS is deemed unsuitable for moving large quantities of data. In the near future, large quantities of engine performance and flight data can be automatically transferred, via Gatelink [9] at airports, to the ground-based Grid system for routine processing [10]. Gatelink is a cost effective, short-range, spread spectrum, broad-band, wireless, microwave datalink that can rapidly move large quantities of data on and off the aircraft.

3.1 The Diagnostic and Maintenance Process

Diagnosis is defined as the act or process of identifying or determining the nature and cause of a fault through the evaluation of symptoms, history and examination. Prognosis is a prediction of a probable course of an emerging fault through evaluation of early symptoms.

A typical scenario is as follows: The on-wing diagnostic system and its associated ground based system are used prior to the use of the Grid-based system. In addition to that initial on-wing diagnosis, the Grid-based system is always used to provide an automated diagnosis. This is desirable because it can detect additional situations such as a recurring errant diagnosis, a new condition that has not yet been uploaded to the on-wing monitoring system, or a condition that can only be detected using tools that require extensive ground-based processing facilities. The resultant automatic diagnoses can then be assessed. In the vast majority of cases normal situations are indicated, however, if a condition is detected with a known cause then appropriate maintenance action can be planned. Additionally, in the rare case that a condition is detected without a clear cause then the situation will be escalated, within the system, to one of various remote experts who can look into the matter further. Using the Grid-based system, they will have access to the data from the current engine flight. They are able to run searches on historical data, get knowledge-based maintenance advice, run signal processing and run simulation tasks to gain an insight into any given event.

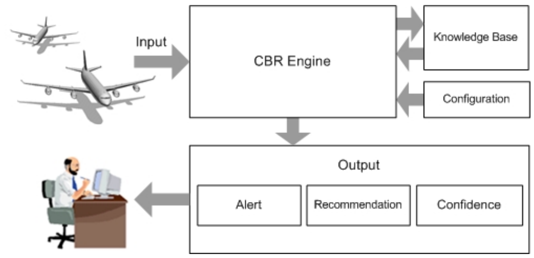

Figure 3. CBR System Architecture

4 CBR for Decision Support

Case-Based Reasoning (CBR) is a knowledge-based, problem-solving paradigm that resolves new problems by adapting the solutions used to solve problems of a similar nature in the past [11, 12]. A further advantage of this approach is that it allows consolidation of rule knowledge and provides a reasoning engine that is capable of probabilistic-based matching. With CBR technology, development can take place in an incremental fashion facilitating rapid prototyping of an initial system. The development of robust strategies for integration of multiple health information sources is achieved using reasoning algorithms of progressively increasing complexity.

In contrast to conventional search engines, CBR systems contain a knowledge model of the application domain in which it operates on. It is therefore not universal but specifically designed for the domain. Hence, it is possible to develop intelligent search abilities, which even show reasonable results when given fuzzy or incomplete requests. Moreover, the results are ranked and complemented by variants and alternatives, thus, not only matches are given but information is valued with "more suitable" or "less suitable". Figure 3 depicts the high-level stages of reasoning in our implementation. However, this does not reflect the actual software architecture. It depicts the functional as opposed to physical configuration. In the following sections, these components are described in further detail.

4.1 Knowledge Base

Essential to our CBR system is the casebase that represents the knowledge repository. This contains detailed descriptions of engine faults and the best practice maintenance advice (solutions) gathered from engineers and experienced mechanics over the development and service life of engines. For a new engine type, little information is known initially but with our CBR technique, a casebase of independent records of fault and maintenance information can be developed in a piecemeal manner and updated as and when knowledge about the behaviour of the engine is known. More importantly, the location of the knowledge base within a virtual maintenance facility on the Grid also allows the integration of diagnostic knowledge from multiple health information sources which are vital in improving the accuracy and coverage of the CBR system. Useful diagnostic information previously available from separate monitoring and maintenance systems, when brought together into a single system, provides for a more powerful diagnostic tool.

4.2 CBR Engine

The primary responsibility of the CBR Engine is to read the knowledge base into memory and perform retrieval, matching and ranking of the cases based on specific query input. The CBR Engine also provides the interface for the system to generate new cases, view and manage existing cases, manage the knowledge model and execute any external modules that contribute to the analysis of information within the system. Retrieval, matching and ranking are performed using an enhanced, weighted nearest-neighbour algorithm of progressive complexity. Using a well defined, internal Knowledge Model of the domain that it operates on, the algorithm effectively emulates how an expert would identify the problem from past knowledge by performing similarity measures across the available information. Although this is done automatically, trained users are allowed to influence the entire process by choosing specific attributes to analyse. They can configure specific weighting of attributes to correspond to the “importance” of each chosen attribute. In addition to that, hard constraints can be defined prior to that so the algorithm can optimise the entire process by reducing the number of potential cases to be matched. With a continuously expanding knowledge base of cases at a global scale, the process described above presents an ever increasing demand for computing resources.

4.3 Recommendation

Traditionally, existing cases in the knowledge base are adapted to form a solution for a new problem. In this diagnostics and maintenance environment, however, the output of the CBR system is delivered in the form of a discrete set of potential candidates as opposed to a single solution. Concern for accountability in a safety-critical environment often dictates that the system not force a user into accepting a single solution. The system aims to recommend a narrowed-down choice of possible solutions, using knowledge accumulated previously about the domain on which it operates. This will enable the user, an aircraft expert in particular, to make an informed decision. In order to do that, each solution is accompanied by the system’s confidence in that answer. Various threshold levels can be tuned to both limit the number of potential solutions as well as eliminate inadequate confidence. Ultimately, the system acts to support the decision making task, but the aircraft expert retains the responsibility for the final decision.

4.4 Confidence

As described above, confidence is one of the critical factors of the CBR system in recommending solutions to the expert. The algorithm will compute the confidence of a solution by taking into account prior knowledge contained in the knowledge model, which includes a model for natural-language terminology, boundary values for each attribute, and attribute relationship models. The process is repeated for each candidate solution to finally obtain a ranked list of recommended solutions. It is important to note here again that a trained user is able to fine-tune the entire process by selecting specific attributes, configuring the weighting of each attribute to correspond to the relative "importance" of that attribute, and also define hard constraints so that the algorithm can further optimise the process.

5 Grid Computing and CBR Deployment

The Grid is defined as an aggregation of geographically dispersed computing, storage and networking resources [2]. It provides many advantages over conventional high-performance computing because it is co-ordinated to deliver improved performance, better utilisation, scalability, higher quality of service and easier access to data. This makes the Grid ideal for collaborative decision support across virtual organisations because it enables the sharing of applications and data in an open, heterogeneous environment. Applications previously considered to be host-centric, such as the CBR system described in the previous sections, can now be distributed throughout a Grid computing system, thus improving quality of service while also offering significantly enhanced capabilities. Our use of industry standard technologies to implement such a Grid-enabled CBR system is discussed here.

5.1 Grid Service

Grid Services are essentially Web Services with improved characteristics such as state and life-cycle management [13]. Our CBR system's functionality has been delivered as a Grid service in a Service-Oriented Architecture (SOA) environment. SOAs are essentially a collection of services, focusing on interoperability and location transparency. These services communicate with each other, and can be seen as unique tools performing different parts of a complex task. Communication can involve either simple data passing or it could involve two or more services co-ordinating some activity. SOAs and services are about designing and building a system using heterogeneous network addressable software components. An important aspect of the service-based CBR delivery is that it separates the service's implementation from its interface.

A typical use scenario for the CBR service is as follows: A Web browser initiates a request to the CBR service at a given Internet address using the SOAP (Simple Object Access Protocol) protocol over HTTP (Hypertext Transfer Protocol). The CBR service receives the request, processes it, and returns a response. Based on emerging standards such as XML (eXtensible Markup Language), SOAP, UDDI (Universal Description, Discovery and Integration) and WSDL (Web Service Definition Language), the CBR service along with other diagnostic services form a distributed environment in which applications, or application components, can inter-operate seamlessly across the virtual organization in a platform-neutral, language-neutral fashion. Consumers of the CBR service are allowed view the service simply as an endpoint that supports a particular request format or contract. Consumers need not be concerned about how the CBR service goes about executing their requests; they expect only that it will.

5.2 High Performance Computing

High performance computing support for the CBR service is provided by means of implementing Open Grid Services Architecture (OGSA) concepts with Web Service technologies. With this, the above-mentioned CBR service has benefited from both Web Service technologies as well as Grid functionality. More specifically, the compute-intensive tasks within the CBR matching process, previously computed on a single computer, can now be aggregated across any available Grid supercomputing node with the use of Grid middleware, the Grid's effective operating system [14]. With this, multiple instances of the CBR service can be generated on-demand. The advantage of this is that it allows multiple consumer requests to be processed simultaneously by separate nodes of the Grid. With our CBR system as a prime example, the integration of Grid computing with Web services has benefited aircraft experts at any remote geographical location by providing them with access to powerful diagnostic tools, data repositories and large computing resources via any Internet-enabled computing device.

6 Grid-Enabled Decision Support on Mobile Handheld Devices

In addition to the typical diagnostic and maintenance scenario described previously, a situation may arise where an aircraft engine expert, usually regarded as a high-value resource, is required to investigate a currently occurring problem under demanding circumstances; i.e. he/she may be traveling to a foreign aircraft site and a conventional computer is not available. Furthermore, the ability of a handheld computer to capture investigative findings on-site and instantly upload these findings to the Grid-based system greatly increases the accuracy of the CBR system in diagnosing the problem. The advantage in rapidly sharing the information across the entire system is that it enables several other engine experts, at different geographical locations, to collaborate in solving the problem, thus reducing aircraft down-time and costs. In the following sections, we discuss the difficulties faced with currently-available mobile, handheld computers and our efforts in developing solutions to these problems.

6.1 Limitations on a Typical Device

A mobile computing device such as the widely available Personal Digital Assistant (PDA) shown in figure 4, presents various problems such as hardware constraints, small graphical display area and security issues. The limited processing power and built-in memory means that applications need to be efficiently implemented. In practice, this will limit the complexity of useable application programming interfaces (API). Software development for a mobile, handheld device tends to be more complicated to account for the device's operating system and individual hardware platform. Furthermore, a small display area usually found on such devices can also make presentation of information to the users a challenging task.

6.2 PDA Demonstrator

In an effort to overcome these limitations, a demonstrator consisting of a PDA that utilises the previously mentioned Grid-based CBR service was designed and implemented. The primary aim of this system was to aid diagnostic and maintenance of gas turbine engines from remote locations under demanding circumstances. The mobile, handheld computing device used in this work is a widely available *HP- iPAQ* PDA. It features, as standard, a built-in 802.11b [15] wireless network adaptor, Bluetooth [16, 17] connectivity and a mini Web browser. Using these, the PDA can to connect to the Internet via a wireless LAN (Local Area Network) or via Bluetooth to a suitable GSM

Figure 4. A Typical mobile handheld PDA

(Global System for Mobile Communications) [18, 19] cellular phone. For the latter option, data transfer using a GPRS (General Packet Radio Service) system [20] on a GSM network is preferred over regular GSM because of the higher bandwidth it provides. This is used to access CBR services available on the Grid. The real advantage of this is that it can offer a user all the benefits of large, global data and high performance applications required in the diagnostic and maintenance scenario.

The limited capacity of PDAs available currently make it impossible to have a complete Globus toolkit equivalent implemented on the device. This necessitates the use of a host-side proxy that will interact with the Grid environment whilst providing suitable access for the device. Here, a mini Web portal, implemented with Apache Tomcat, is used as the proxy, enabling access for the device to Grid services using a standard, built-in mini Web browser that acts as the client to the proxy. The mini Web browser represents the front-end for the user on the PDA.

The mini portal is very similar to a standard portal accessed by conventional desktop computers, the primary difference being that the mini-portal is simplified by removing complex script functions normally aimed to enhance the layout of content on larger displays. Furthermore, the page layouts are rearranged such that each page would only execute a single CBR operation at a time, both for display purposes and to optimise on bandwidth usage. In an evaluation of the mini portal against a standard web portal, it has been found that the mini portal can deliver an identical quality of results to the user whilst minimising the graphical content load on the PDA display. An Apache Tomcat servlet container serves as the hosting environment for the mini portal on any Grid node.

The software and communication standards used in the demonstrator systems that have been implemented are based on widely accepted industry standards thus it is highly feasible for the system to be migrated across various other application areas. Furthermore, the increasing availability of wireless networks [17, 21] and advances in Grid technology provide a strong case for mobile, Grid-enabled decision support with handheld computing devices.

In the following sections, the CBR system, Grid computing and mobile PDA work described thus far are implemented in two different areas of the aero engine diagnostic and maintenance scenarios – pro-active remote condition monitoring and fault investigation.

6.2 Pro-Active Remote Condition Monitoring

Condition monitoring systems are synonymous with fault diagnostics. Whether localised or distributed, they are common and widespread, with more and more organisations becoming dependant on such systems to support critical decision making in order to identify problems quickly, avoid unnecessary risks and reduce cost.

In the past, centralized high-performance ground-based systems have the ability to support powerful applications but they are limited in their scope of reach or can prove inaccessible when and where they could be most effective. At the opposite end of the scale, portable or on-board standalone systems can be very useful in remote locations or harsh operating environments but they are very limited in terms of performance and capacity.

Today, the integration of service-oriented architectures, modern wireless technologies, advanced mobile devices and distributed computing presents a unique solution to overcome these limitations. This integration can provide the necessary high-performance computing capability required to continuously perform condition monitoring whilst transmitting essential information back to key users via a mobile handheld device. Figure 5 depicts a screen capture of this on a PDA that was implemented as part of our work. Here, possible causes of the occurring problems on different aircraft have been successfully identified. Note that any references to actual aircraft or operators have been anonymised.

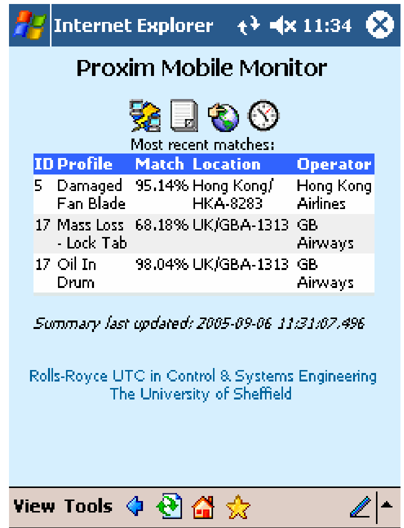

Figure 5. Fault alert and diagnosis

The prime advantage of this approach is that any occurring problem condition can be made known immediately to the right person, in the right place at the right time, giving that person the opportunity to pro-actively handle the arising problem condition and collaborate on-line with a virtual network of experts to solve the problem. Complementary analysis tools and services on the Grid allow a widespread collection of knowledge, data and tools that were not previously available in this manner to be used on-line for further investigation. It is this model of problem-solving that we define here as pro-active mobile computing for decision support.

The condition monitoring demonstrator system has been implemented using a network of remote CBR service nodes deployed at different geographical locations. This will be described in close detail in Section 7. These remote nodes continuously receive diagnostic information, downloaded from aircraft on-wing systems, from multiple sources in real-time. Any newly received information will be automatically analysed to identify problems.

A particularly unique feature of our distributed architecture is the ability to monitor health information across multiple nodes, at different locations, without actually transmitting that information off-site. In the event of a problem, alert messages can be automatically flagged to notify remote users via suitable communication channels based on the severity of the problem. At this point, the actual exchange of information between stakeholders can then be negotiated via established, trusted channels for further action based on the organisations’ requirements and service-level agreements. A clear advantage of this approach is the significant reduction in the network bandwidth required. But more importantly, it further supports crucial security policies and privacy of any commercially sensitive data.

6.3 Pro-Active Fault Investigation

For a more user-driven, interactive fault investigation process, the PDA-based mini browser can be used to transmit specific user inputs to the CBR service in order to match the details of a currently occuring problem against the large CBR knowledge base on the Grid. Figure 6 depicts the match results of such a process on the PDA. For any new or existing case, additional knowledge gained from further analysis such as vibration spectral data, as depicted in figure 7, digital images or even audio/video media can be appended to the case in real-time as it is being investigated. This makes the information available for immediate use by other experts across the Grid and if necessary, escalated to another expert at a different location for futher investigation. Finally, problems that have been identified and the successful solution to that problem can be appended to the case, on-line, via the same interface. This will be stored in the CBR knowledge base on the Grid as new knowledge for future use (figure 8).

To further support the diagnostic process, engine performance simulations, normally a compute-intensive and time consuming task, can be executed using an Engine Simulation Grid Service (ESGS) [22]. The results of this can then

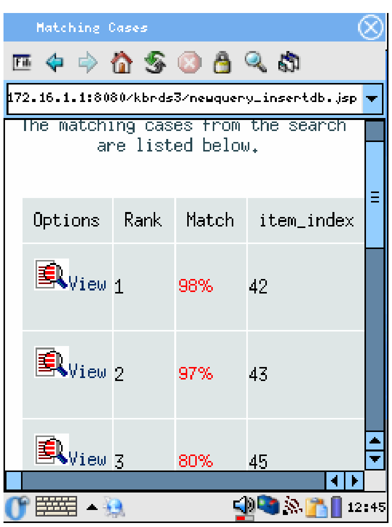

Figure 6. Pro-active fault investigation

be retrieved on the mobile device. This facility has been made available on our PDA demonstrator system, as presented in figure 9. Depicted in this figure is crucial information relating to a particular event, which was later identified by engine experts as a situation where an abnormal spike occurred in the engine data due to a bird-strike. In this situation, a large bird is accidentally ingested by the engine whilst in flight. Such an occurrence usually goes unnoticed by the pilot or aircraft operator, but can potentially damage to the engine's internal components. With this available knowledge, a remote expert may decide to monitor the engine more closely and arrange for a boroscope inspection of the engine's internals at the next convenient landing location.

7 Proxim-CBR Grid Service Network

In order to support the pro-active diagnostic and maintenance process, the Grid-based CBR system is made up of a scaleable network of CBR services. Three different types of CBR nodes exist within the system. Each node is deployed as a Grid service on a remote host computer. Figure 10 depicts these node types and their relationship in the node network. Their details are described in the following sections.

7.1 Proxim Service Node

The Proxim Service Node, as depicted in figure 10, is located at the back-end of the node hierarchy. This node is typically deployed at the geographical location where data is first captured in the system. It contains a CBR Engine and hosts a repository of cases local to this node. When requested by a Proxim Broker Service Node, this node will perform a search, match and rank process at a local level. It then returns a summary of results to the requesting broker. This node is also responsible for delivering complete case records to a human user via the broker. However, the latter function is subject to the user being granted appropriate access rights to that complete record.

7.2 Proxim Broker Service Node

The Proxim Broker Service Node maintains a comprehensive registry of all available Proxim Service Nodes. When requested by a Proxy Service Node, it will initialize and orchestrate a search, match and rank process across all the available Proxim Service Nodes. Individual sets of match results received from every Proxim Service Node are collated to form a single result summary. A summary will also include essential information needed to retrieve an individual result case in full detail when required. For interactive, fault investigation purposes, queries can be submitted to the Proxim Broker Service Node directly from the CBR portal on the Internet. For automated condition monitoring purposes, a Proxy Service Node is deployed to automatically initialize and manage multiple queries to the Proxim Broker Service Node. When any query is submitted, the CBR system effectively views the distributed collection of remote data as a single, virtual repository.

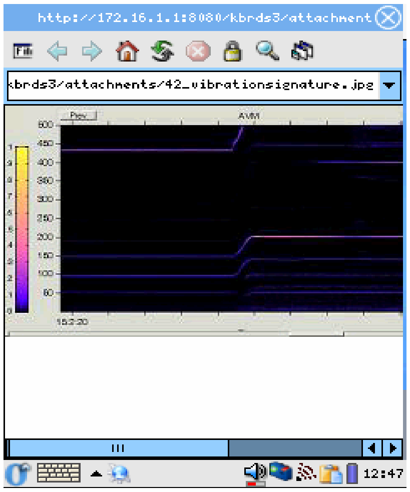

Figure 7. Engine vibration spectral data

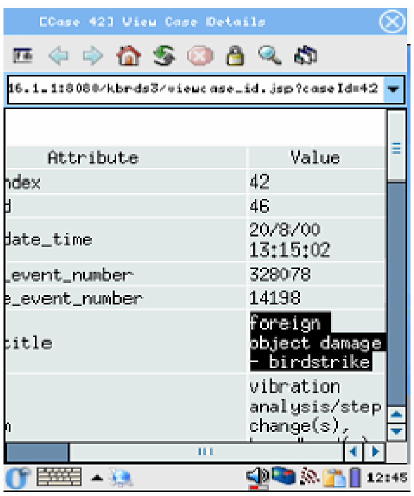

Figure 8. Full fault case details

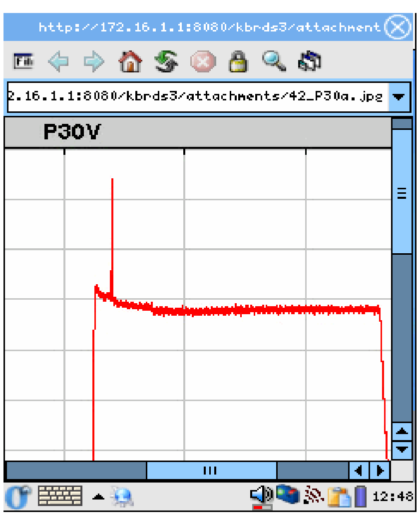

Figure 9. Abnormal spike in engine data identified via the Engine Simulation Grid Service

7.3 Proxy Service Node

A Proxy Service Node contains a repository of query profiles. Each profile represents a known problem condition or engine event description. It also maintains a registry of available Proxim Broker Services. With these in place, the node will automatically initialize and manage query processes to an available broker to identify problem conditions. Depending on the requirements of the application, this can be configured to execute at automatic intervals or in a continuous manner. Result summaries generated by the Proxim Broker Service are stored in the Proxim Mobile Monitor Service. This will be presented via a PDA to a human user, in particular an aero engine expert, whenever and wherever required. It is important to note here that there may exist more than one Proxy Service Node, each one will support queries to single or multiple brokers at different locations. When deploying multiple Proxy Service Nodes, the functionality to be supported by each node is determined by the needs of the intended application domain or by specific, unique areas of a particular system being monitored. For example, there could be many proxies operating on different components of an aircraft at different intervals. In another example, a proxy could be deployed specifically for, and wholly owned by, an individual or organisation that has query profiles representing knowledge of some commercial value.

8 Security

The dynamic and multi-institutional nature of Grid environments introduces challenging security issues that demand new technical approaches [23]. For instance, the CBR knowledge base and related engine diagnostic

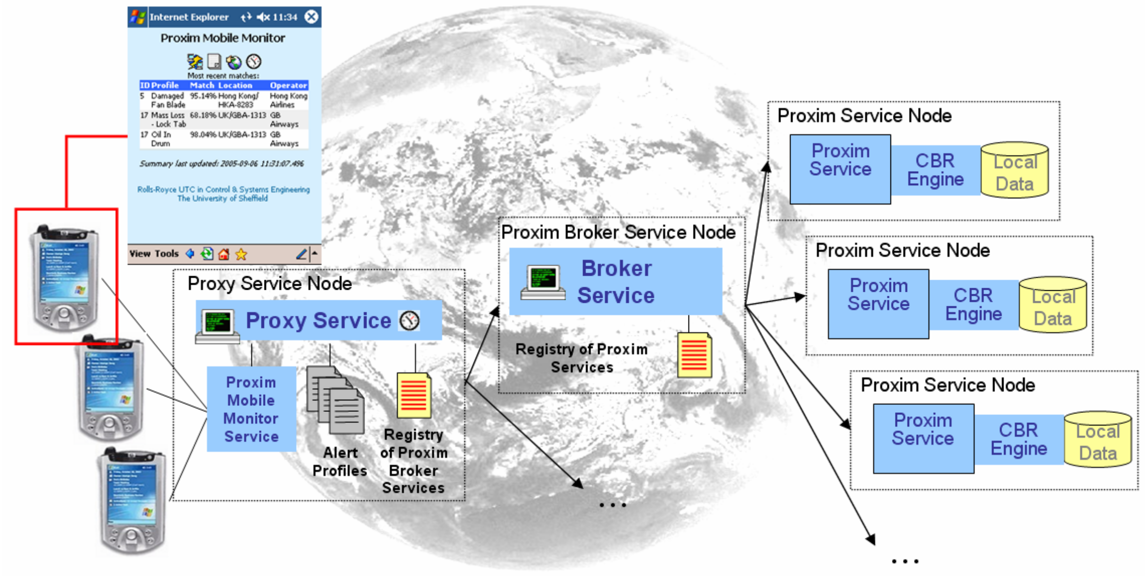

Figure 10. Scaleable Proxim-CBR Grid Service Network

data could contain highly relevant information about an engine's design characteristics and operating parameters. This could potentially be misused. For this reason, access to the systems described here is highly restricted to authorised users only. To overcome the problem, the Grid Security Infrastructure (GSI) provided by the Globus Toolkit has been used to enable secure authentication and secure communication over an open network. GSI is composed of security elements that conform to the Generic Security Service API (GSS-API), which is a standard API for security systems promoted by the Internet Engineering Task Force (IETF).

GSI consists of a number of security features that include mutual authentication and single sign-on. This is based on public key encryption, digital certificates and Secure Sockets Layer (SSL) communication. At the core of the security infrastructure is authorisation based on X.509 digital certificates for both service consumers and service hosts. Hence, all users and service hosts need to acquire a certificate issued by a trusted Certificate Authority (CA). The bottom line is that any user, regardless of his/her physical location, will be barred access to any resource on the system unless their credentials have been successfully verified.

9 Conclusions and Future Directions

The capability displayed by the PDA demonstrator system is particularly important because it offers aircraft experts, considered as a high-value resource, the mobility to pro-actively operate on large data and complex problems in an “anytime and anywhere” manner. With CBR technology, problem identification in health monitoring is not limited by a set of rules, but the overall "closeness of match" and ranking of a problem condition can be identified. In some situations, this may be used to prompt an investigation to facilitate early detection or on-condition monitoring. In the longer term, CBR will contain a constantly growing repository of event knowledge that represents a very valuable knowledge asset for the domain operator.

Similar scenarios commonly occur across a diverse range of domains and this includes engineering, healthcare and finance. However, regardless of the application area, each system shares a number of similar operating and design characteristics, making it possible to experience the similar benefits of Grid-enabled, pro-active mobile decision support. One such area is large-scale monitoring of patient health. Using Proxim-CBR, a medical expert could potentially have the capability to continuously monitor the condition of multiple patients at different geographical locations whilst maintaining the privacy of their medical records.

Our work in this paper has demonstrated that Grid-enabled computing from mobile devices can be very effective in a decision support environment. The real advantage of service-oriented architectures is that it enables business/engineering processes to be examined so that services can be provided to 'accurately and sufficiently' support core operations. In the past, there has been a tendency for organisations with complex activities to be burdened with unnecessary bureaucracy and/or insufficient timely information/detail. If engineered correctly, scaleable Grid service networks, such as Proxim, have the potential to liberate enterprises into more effective and dynamic management of their processes, and they no longer have to force-fit a "one size fits all" solution to their problem. Each architecture solution can be specific, and this is where pro-active mobile computing can be particularly powerful, i.e. in some situations, say in bedside medical treatment, it has not been possible to have powerful diagnostic support tools and information, despite the fact that is where indeed the support/tools are most needed. The real achievement of the Proxim-CBR PDA condition monitoring demonstrator presented here is that there is now the opportunity to properly support processes that have always needed mobile decision and information support. The work presented in this paper extends the range of process support to where it is most needed, i.e. where the work is being done.

Acknowledgements

This project is part-funded by a Collaborative R&D grant under the DTI Technology Programme. Further information can be found at www.dti.gov.uk/technologyprogramme. The authors gratefully acknowledge contributions from Rolls-Royce plc and partners of the BROADEN project.

References

[1] Rolls-Royce. “The Jet Engine”, Rolls-Royce Plc, 1986.

[2] I. Foster (Ed.) and C. Kesselman (Ed.), “The Grid 2”, Morgan Kaufmann, 2003.

[3] S.M. Hargrave. “Evaluation of Trent 800 Portable Maintenance Aid Demonstrator”, Rolls-Royce University Technology Centre, University of Sheffield, Report No. RRUTC/Shef/R/98202, 1998.

[4] S.M. Hargrave. “Review of Performance-Based Diagnostic Tool”, Rolls-Royce University Technology Centre, University of Sheffield, Report No. RRUTC/Shef/TN/98204, 1998.

[5] Distributed Aircraft Maintenance Environment (DAME) project; www.cs.york.ac.uk/dame, 2003.

[6] T. Jackson, J. Austin, M. Fletcher, and M. Jessop. “Delivering a Grid enabled Distributed Aircraft Maintenance Environment (DAME)”, Proc UK e-Science All-Hands Meeting, pp. 420-427, 2003.

[7] Business Resource Optimisation for Aftermarket and Design on Engineering Networks (BROADEN) project; www.shef.ac.uk/acse/research/themes/utc/broaden.html, 2005.

[8] G.F. Tanner and J.A. Crawford. “An Integrated Engine Health Monitoring System for Gas Turbine Aero-Engines”, Proc. IEE Seminar on Aircraft Airborne Condition Monitoring, pp 5/1-5/12, 2003.

[9] J. Croft. “Avionics: Beaming Bits and Bytes”, Air Transport World, p. 54, January 2006.

[10] H.A. Thompson, "The Use of Wireless and Internet Communications for Gas Turbine Engine Monitoring and Control", Proc AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Years, July 2003.

[11] J. Kolodner. “Case-Based Reasoning”, Morgan Kaufmann, 1993.

[12] S.K. Pal, T.S. Dhillon and D.S. Yeung (Eds). “Soft Computing in Case Based Reasoning”, Springer-Verlag UK, 2000.

[13] I. Foster, C. Kesselman, J. Nick, and S. Tuecke. “Grid Services for Distributed System Integration”, Computer, 35(6), 2002.

[14] I. Foster and C. Kesselman. “Globus: A Metacomputing Infrastructure Toolkit”, Intl J. Supercomputer Applications, vol. 11, no. 2, pp. 115-128, 1997.

[15] IEEE 802.11 Working Group, “The IEEE Std 802.11b-1999”, 1999.

[16] IEEE 802.15 Working Group. “The IEEE Std 802.15.1-2002”, 2002

[17] A. Vollmer. “With Devices Ready to Go, Bluetooth is Poised to Make Its Move”, Electronic Design, July 24, 2000.

.

[18] M. Mouly and M. Pautet. “The GSM System for Mobile Communications”, Published by the authors, 1992.

[19] M. Rahnema. “Overview of the GSM System and Protocol Architecture”, IEEE Communications Magazine, vol. 31, no. 4, pp. 92-100, April 1993.

[20] R. Kalden, I. Meirick, and M. Meyer, "Wireless Internet Access Based on GPRS," IEEE Personal Communications Magazine, vol. 7, no. 2, pp. 8-18, April 2000.

[21] U. Varshney. “Recent Advances in Wireless Networking”, IEEE Computer, vol. 33, no. 6, June 2000.

[22] X. Ren, M. Ong, G. Allan, V. Kadirkamanathan, H.A. Thompson and P.J. Fleming. “Service-Oriented Architecture on the Grid for Integrated Fault Diagnostics”, Journal of Concurrency and Computation: Practice and Experience, John Wiley and Sons, 2006.

[23] V. Welch, F. Siebenlist, I. Foster, J. Bresnahan, K. Czajkowski, J Gawor, C. Kesselman, S. Meder, L. Pearlman, and S. Tuecke. “Security for Grid Services”, Proc. 12th IEEE Int’l Symposium on High Performance Distributed Computing (HPDC-12), pp. 48-57, IEEE Press, 2003.

Figure Captions

Figure 1. A Rolls-Royce Gas Turbine Engine

Figure 2. Structure of the Flightline Maintenance Advisor

Figure 3. CBR System Architecture

Figure 4. A Typical mobile handheld PDA

Figure 5. Fault alert and diagnosis

Figure 6. Pro-active fault investigation

Figure 7. Engine vibration spectral data

Figure 8. Full fault case details

Figure 9. Abnormal spike in engine data identified via the Engine Simulation Grid Service

Figure 10. Scaleable Proxim-CBR Grid Service Network