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An Integrated Process for System Maintenance, Fault Diagnosis and Support[1]

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Abstract— This paper presents an overview of an integrated process for system maintenance, fault diagnosis and support. The solution is based on Qualtech System, Inc.'s (QSI's) TEAMS toolset for integrated diagnostics and involves several key innovations. As a showcase of the integrated solution, QSI, along with Antech Systems and Carnegie Mellon University (CMU), have recently completed a research project for the Information Technology Branch at the Naval Air Warfare Center–Aircraft Division (NAWC-AD) in St. Inigoes, MD. The project involved enhancing, customizing and integrating the QSI toolset with interactive electronic technical manuals (IETMs), whose display automatically adapts to the technical capabilities of the technician using the system. The entire system, termed ADAPTS (Adaptive Diagnostic And Personalized Technical Support), provides a comprehensive solution to integrated maintenance and training. This paper describes the architecture of different QSI modules and their overall integration into a comprehensive system maintenance, diagnostic and support system, as implemented in the ADAPTS system.

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INTRODUCTION

As technology advances, there is a significant increase in the complexity and sophistication of systems, while integration and miniaturization have sharply limited access to test points. Thus, the number of possible failure sources has increased, while the number of monitoring points has decreased, resulting in reduced fault observability. Consequently, system maintenance presents formidable challenges to manufacturers and end users of complex systems, such as combat aircraft, helicopters and reusable launch vehicles (RLVs), consisting of electronic, electromechanical and hydraulic subsystems. Indeed, the maintenance cost over the lifetime of many systems far exceeds the manufacturing cost.

From a design perspective, it has been well established that a system must be engineered simultaneously with three design goals in mind: performance, ease of maintenance, and reliability [1]. To maximize its impact, these design goals must be considered at all stages of the design—concept $\rightarrow$ design of subsystem $\rightarrow$ system integration. Ease of maintenance and reliability are improved by performing testability and reliability analyses at the design stage. In addition, once the system is fielded, efficient preventive maintenance, on-line system health monitoring and smart diagnostics and repair strategies need to be developed. For example, in mission critical operations, it is imperative that an inoperable system be quickly diagnosed and repaired as soon as possible. In order to contain the costs of such operations, it is imperative that the fault be isolated and one not indulge in the guessing game of "swapotronics", which only tends to increase Retest OK (RTOK) rates and thus increases the operational costs many-fold. In a well-designed integrated maintenance system, on-board real-time diagnostic solutions should be able to reduce the ambiguity, if not isolate the fault, so that ground level diagnostics is reduced to a minimum. Indeed, the suspect set of faulty components or the isolated component information can be relayed to the ground station even before the aircraft lands. By having the list of possibly faulty parts ready to be installed when the aircraft lands, ground supply requisition, repair and replacement procedures can be speeded up to further reduce the operational costs. Thus, an efficient product design for ease of maintenance and reliability coupled with an integrated process for intelligent system maintenance and logistics support, can achieve significant savings in the total life-cycle cost of a product, improve the system availability and increase the sortie-generation capability.

As part of the ADAPTS system, the integrated toolset of QSI was modified and enhanced to implement such an integrated maintenance system. A primary focus of the project was to develop a human-centered, adaptive, diagnostic environment utilizing QSI's interactive diagnostics tool, TEAMATE, and CMU's Adaptive Server to dynamically generate browsable, user-tailored, adaptive content for the technician.

THE INTEGRATED TEAMS TOOLSET AND ITS DEPLOYMENT IN ADAPTS

Motivated by the need for an integrated process for system maintenance and diagnostics in complex systems, current research at QSI is focused on enhancing the TEAMS toolset to include a fully operational support process for on-line diagnostics, portable maintenance aiding, the current Navy operational procedures, parts prediction and inventory management. The integrated process not only eases the model development process by integrated model management with the model development tool, but also integrates data from field maintenance to update and improve the models for better fault detection and isolation, as well as improved diagnostic strategies. The process maintains profiles of available technicians and improves on the diagnostic strategy by taking into account their dynamic skill levels. QSI's integrated toolset comprising of TEAMS™ (Testability Engineering and Maintenance System), TEAMS-RT™, TEAMATE™ and TEAMS-KB/KB-lite™ captures the users' knowledge of the system in terms of models to automate the testability and reliability analyses, and to perform on-line monitoring and off-line diagnosis tasks. The tools combine to form the core piece in the ADAPTS integrated maintenance system.

TEAMS

TEAMS is a graphical software tool for diagnostic model development and analysis [1] that integrates a unique multi-signal flow graph modeling methodology [2, 3] and various analysis techniques for performing testability analysis and design for testability [4]. Various testability figures of merit (TFOMS) are also generated. TEAMS has been used for testability analysis of large systems containing as many as 50,000 faults and 45,000 test points. TEAMS minimizes the life-cycle cost of a system by aiding the system designer and test engineer in embedding testability features, including "built-in-test" requirements, into a system design; and by aiding the maintenance engineer by developing near-optimal diagnostic strategies. TEAMS is used to: (i) model individual subsystems and integrate them into system models, (ii) analyze and quantify testability of systems and subsystems, visually pinpoint the diagnostic inefficiencies of a system, and make recommendations towards the design of completely testable systems, (iii) provide a comprehensive aid to automate the generation of FMECA reports, (iv) generate near-optimal diagnostic procedures for a variety of realistic testing options. Thus, TEAMS is mainly a design for testability (DFT) tool, but its (pre-computed, and, hence, static) diagnostic procedures can be embedded into Interactive Electronic Technical Manuals (IETMs) and Automatic Test Equipment (ATE). The SGML-based diagnostic strategy has allowed Sikorsky to produce automated technical publications that are consistent with IETMs and expert diagnostic systems for a range of aircraft configurations. TEAMS is being used by Boeing, Sikorsky, Lockheed-Martin and others in the V22, F22, Comanche, and other projects primarily for DFT. In the ADAPTS project, TEAMS was used extensively to model the designated system, the Sonar subsystem of the SH-60F helicopter. It was also used, along with TEAMATE, to validate the model. The flat SGML file generated by TEAMS from a file format for TEAMS model specified by Sikorsky Aircraft, was used to develop the binding between the identifiers of the individual entities in the model of the Sonar subsystem to the relevant content in the IETM for that entity.

TEAMS-RT

TEAMS-RT is a real-time companion tool to TEAMS for on-board diagnosis and on-line system health monitoring [1]. It takes as inputs a TEAMS model of the system and on-board smart-sensor processing results on system health (the results may be asynchronous). TEAMS-RT then identifies the known bad, known good and suspect set of components. Some unique features of TEAMS-RT are : (i) efficient real-time processing of sensor results, (ii) update of fault-test point dependencies in response to system mode changes, and (iii) update dependencies resulting from failures in redundant components. TEAMS-RT may be embedded in the flight computers to continuously monitor the health of the system, and identify any in-flight failures. The real-time capabilities of TEAMS-RT have been demonstrated on X33 Integrated Propulsion Testbed Demonstrator project: it took only 50-100 milliseconds/second to monitor a 1000 component and 1000 test liquid oxygen (LO_2) and liquid hydrogen (LH_2) subsystems on a space-qualified Sparc2 workstation. Memory requirements were 0.9 MB. TEAMS-RT real-time and memory performance exceeded the specifications (execution time specification: 200msec; memory specification: 2MB). TEAMS-RT is the real-time diagnostic module that can be placed onboard an aircraft for continuous fault monitoring and the generation of system health status.

The TEAMS-RT software has a modular structure; it is composed of two primary modules - a kernel (the diagnostic engine) which exists as a dynamically linked library (DLL), and a driver routine, which acts as the executive. The driver routine utilizes the Application Programming Interface (API) of the TEAMS-RT kernel to perform different tasks that are application specific, including any user interface, if required.

In the SH-60F helicopter, chosen for the ADAPTS project, the MIL-STD-1553 databus [5] is used to connect the various electronic subsystems including the Sonar. The built-in-test (BIT) results for the different electronic subsystems were obtained by direct communication with the subsystem through the 1553 bus. A notebook computer running TEAMS-RT to communicate with the bus uses a PCMCIA card, developed by ILC DDC Corporation. The software to interface TEAMS-RT with the drivers of the PCMCIA card to access the 1553 bus was developed as a separate library and was linked to the driver routine. The interface software was developed with a modular architecture with one part of the software responsible for constructing the message words and the minor and major frames according to the specifications set by Sikorsky Aircraft for the particular device being polled. The other part is responsible for decoding the data received from the card driver and interpreting it in terms of a problem with communication through the bus or a problem with the device itself. Each of these problems represents a test in the context of the TEAMS model of the subsystem being diagnosed. The failed test or tests are used by TEAMS-RT to generate a system health report and to log it in a mobile database, namely TEAMS-KB-lite, residing in the notebook computer. This system health report is used by TEAMATE for off-line diagnosis.

TEAMATE

TEAMATE (read team-mate) is a companion tool to TEAMS and TEAMS-RT for adaptive field diagnosis [1]. TEAMATE is a thin-client capable, network-based environment for interactive diagnosis. It takes the guesswork out of troubleshooting by identifying the failure source(s) in the shortest possible time, subject to various constraints on available resources, setup operations already performed, the initial suspect set generated by TEAMS-RT and pilot debrief. TEAMATE can also operate in a training mode and is ideal for trainees and apprentices for learning troubleshooting strategies and repair procedures. The diagnostic engine is integrated with an interactive electronic technical manual (IETM) to assist field personnel in pre-flight checkouts and post-flight repairs. TEAMATE employs TEAMS-generated system models to perform interactive diagnosis.

In the ADAPTS system, TEAMATE is implemented as a server and a Java applet client. The client forms an integrated part of the entire ADAPTS client interface. The technician performs off-line diagnosis with TEAMATE and interacts with the user interface of the TEAMATE client. The client performs minimal processing of user inputs and values and messages returned by the server, thus retaining a thin-client structure. The client user interface allows the user to pass/fail a test, indicate the completion of a setup, undo the last step which could be a test or a setup, or state that a step (i.e., a test, setup) suggested by TEAMATE cannot be done. In addition, to this simple set of options, the user interface allows a number of advanced options that the technician can use to further customize the operating state of a diagnostic session and manipulate the test strategy being generated dynamically by TEAMATE. Among the many advanced options are the ability to change the pass/fail status of any test that is not complete or not suggested by TEAMATE, change the availability status of any resource, indicate the inability to perform any test or setup that is not yet complete, and change the diagnostic status of any component. Thus, TEAMATE allows a great degree of flexibility and adaptability to operating conditions of a diagnostic session.

TEAMS-KB

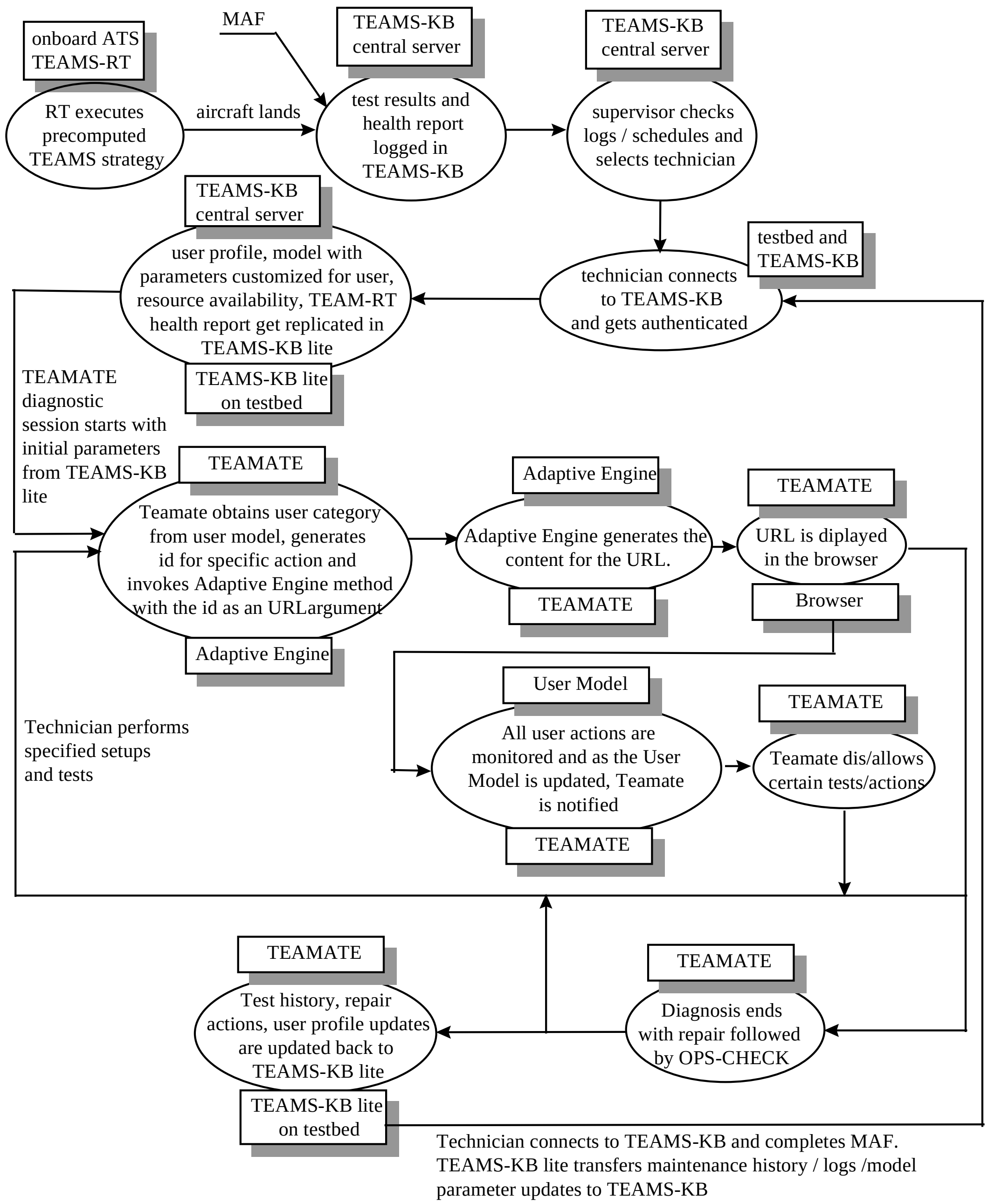
TEAMS-KB is a maintenance database tool that can be deployed at various maintenance sites [1]. It provides the glue to the entire diagnostics and maintenance process, and makes the promise of an integrated diagnostic process a reality. TEAMS-KB provides a repository for TEAMS and TEAMS-generated models. In addition, the on-line diagnostic and maintenance information collected by TEAMATE (components repaired, repair times/costs, test costs/times, etc.) is archived by TEAMS-KB. It also archives diagnostic/maintenance data from external maintenance management databases, legacy/provisioning databases, or through TEAMS-KB's rich, user-friendly graphical interface forms. TEAMS-KB has various parameter estimation algorithms built into it for the analysis of maintenance data. It can be used to further refine the system model residing in the knowledge base of TEAMS with updated repair costs, repair times, component failure rates and diagnostic costs and times. In addition, the analysis algorithms of TEAMS-KB can be invaluable at the maintenance site, since they also provide predictions of optimal shelf-stocks of spares, and parts requirements. The reports generated by TEAMS-KB can provide insights into the bottleneck operations that slow down the entire maintenance process, by flagging unreasonably long task times, repeated failures of certain components, and updating hazard rates of components caused by changing environmental conditions.

TEAMS-KB-lite is a portable database with a small memory footprint that works in conjunction with TEAMS-KB. It is used for field deployment and is used as a temporary repository for TEAMATE data (models and TEAMATE logs) that are uploaded to TEAMS-KB through automatic or manual scheduling. In the ADAPTS project, it also acts as a temporary repository for the downloaded

TEAMS-RT data that TEAMATE uses as the initial suspect set during off-line diagnosis.

TEAMS-KB and TEAMS-KB-lite maintain and process several maintenance actions and operations, such as the Maintenance Action Form (MAF) and Supervisor Action Forms. TEAMS-KB, the central database, is also a complete repository of TEAMS models, whose parameters, such as test costs, test times, mean-time to failure (MTTF) of parts, repair costs, repair times are updated from the data logged by TEAMATE in the mobile TEAMS-KB-lite database. In addition, TEAMS-KB tracks parts inventory, performs parts prediction and parts ordering based on current stockage levels. Currently, TEAMS-KB is an Oracle 8.0 Enterprise Edition database for hosting on a server computer at the ground station. TEAMS-KB-lite, an Oracle-lite 3.0 database

Overview of event-flow in the Integrated Maintenance Assistant



***Note** : Each event is described in the ovals and the modules attached to the upper and lower sides represent a server-client relationship in the context of that event. In some cases the event described is internal to the module.*

Figure 1: Workflow in a generic integrated diagnostic and maintenance system

with a small memory footprint, is ideal for mobile and other hand-held computer devices. It is currently hosted on a notebook computer that the technician will carry in the field as the Portable Electronic Display Device (PEDD). Data is exchanged and updated between TEAMS-KB and TEAMS-KB-lite based on the replication and refresh capabilities built into those databases.

Thus, in the ADAPTS effort, we leveraged the TEAMS toolset for automated multi-signal dependency modeling from legacy data (via TEAMS), on-board diagnostics using built-in-tests (via TEAMS-RT), portable intelligent maintenance aiding, automated and consistent technical publications and linking with interactive electronic technical manuals (via TEAMATE), and maintenance procedures, data collection and data mining (via TEAMS-KB).

INTEGRATED WORKFLOW

Figure 1 shows an example of the workflow in the ADAPTS process and how the different modules of the TEAMS toolset subsume the various functions in an integrated environment. The workflow described is generic, with the exception of the Adaptive Engine that generates the adaptive content. Consequently, it is applicable to other maintenance scenarios as well.

Figure 2 describes the overall architecture of the integrated diagnostic and maintenance process developed for the ADAPTS system. Figures 2 and 3 combine to describe the information flow among the various modules and the protocols implemented for information transfer among these modules to satisfy the hardware and software constraints imposed by the ADAPTS system in a real deployment mode.

The overall work and information flow concept is as follows: The maintenance procedure starts with the initiation of an electronic Maintenance Action Form (MAF) resident in TEAMS-KB. The MAF can be initiated by the pilot (unscheduled maintenance) or by the Maintenance Control department (scheduled maintenance). The supervisor is electronically notified when she/he logs into the TEAMS-KB system. Based on the availability and expertise level of the technicians, the supervisor assigns a technician to service the aircraft undergoing maintenance. When the assigned technician logs on, she/he also gets notified of the awaiting jobs. Based on the discrepancy report, the technician chooses the required toolbox. The appropriate model for the system to be diagnosed and the corresponding database tables for the technician's current profile (the user model) are replicated/refreshed on the PEDD that the technician will use at the repair site. In addition, the system health report generated by TEAMS-RT for the current maintenance scenario, if available, will also be replicated on the PEDD. In the case of the ADAPTS system, the PEDD may be connected to the network at the repair site or it could be stand-alone. The PEDD chosen for the ADAPTS system is a notebook computer capable of running the server modules of the ADAPTS system and the Oracle-lite database, namely TEAMS-KB-lite. The ADAPTS system on the PEDD, configured appropriately, is fully functional despite the absence of network connectivity at the repair site. However, for the subsequent model parameter and the user profile update to TEAMS-KB (the central repository), the PEDD is connected to the network.

At the repair site, the technician has the option of reviewing

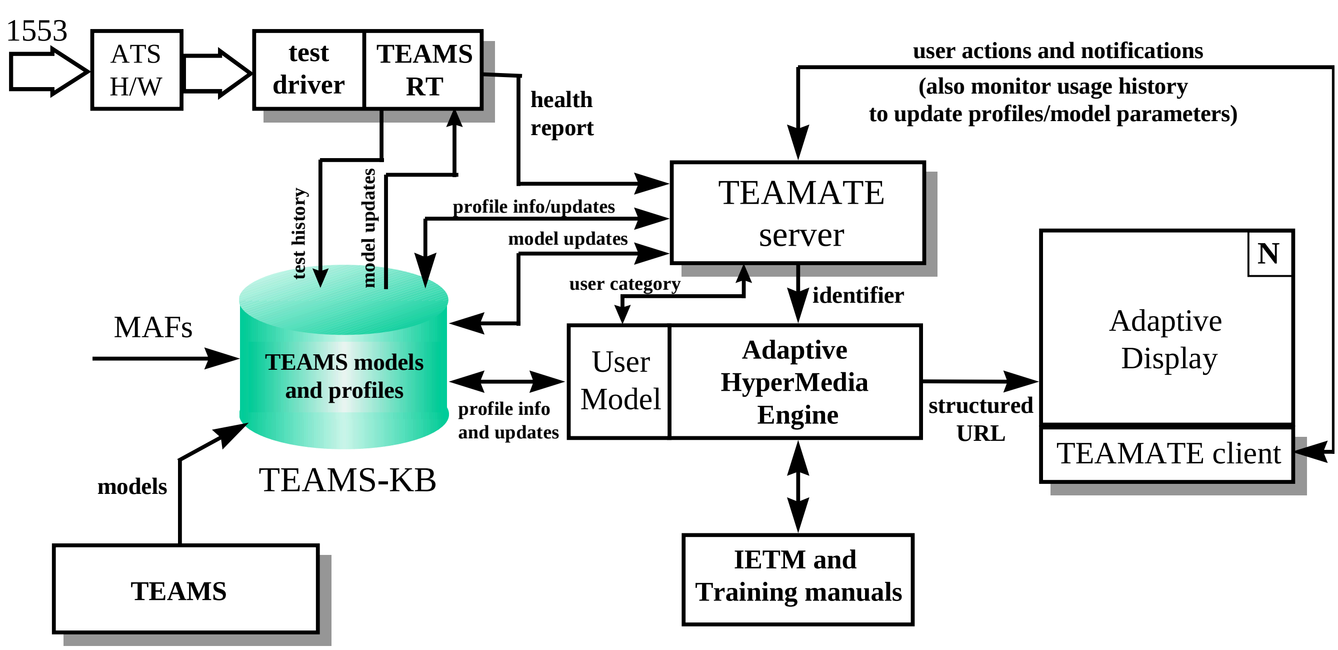


Figure 2: Overall architecture of integrated diagnosis and maintenance as implemented in ADAPTS

the discrepancy and/or reviewing the system health report from TEAMS-RT and initiating the diagnostic process via TEAMATE. TEAMATE reads the discrepancy filed in the MAF and the system health report from TEAMS-RT and configures itself to the appropriate state and starts the diagnostic process. Based on the login identifier of the technician, TEAMATE obtains the user's general skill level from the user model for repairing the system. The skill level takes into account the user's familiarity, i.e., prior experience with the system both in training and diagnostic modes. Based on the skill level of the user, TEAMATE adjusts the costs associated with various tests and dynamically adapts to the user's experience with the particular system. Next, TEAMATE executes its algorithms and generates the identifier of the next operation to perform. In the ADAPTS system, the TEAMATE client exists as a Java applet that runs within a dedicated client application with a browser control. The TEAMATE client receives the identifier of the next step, constructs a structured URL that consists of the identifier as an argument and a command to the Adaptive Server to generate the content for the URL in the frame specified for the adaptive content. The web server invokes the Adaptive Server with the command and the arguments. The Adaptive Server obtains the identifier from the arguments and uses a mapping from the identifier to the electronic IETM to generate the HTML content. It also obtains the user's characterization factor from the User Model database and adapts the content for the specific technician and displays it in the appropriate frame of the browser window. Further details regarding generation and display of the adaptive content is in the companion paper [6].

The technician can explore the adaptive content and perform the task suggested by TEAMATE. The task can be a setup operation or the test action itself. The technician notifies the TEAMATE client of the completion of a task. The technician, at any time during the process, has the option of undoing any number of steps, indicating that a setup or a test cannot be done, changing the pass/fail status of any test not completed or not yet suggested by TEAMATE, completion status of any setup, availability of any resource and any test, and the status of any component. After TEAMATE has isolated the fault, it suggests the repair-and-replace procedure of the faulty component, followed by an operational check to ensure that the entire system is indeed fault-free after the repair and replacement procedure. During the repair and replacement procedure, the technician can utilize the MAF form to indicate the part to be replaced and can issue a requisition from the Supply department. The Supply department gets notified of the requisition and can initiate the process of acquiring the required part. During this period, the MAF is in the Awaiting Maintenance (AWM) mode and the technician saves the current TEAMATE session and has the option of resuming other duties. When the Supply department records the arrival and delivery of the part to the repair site, the technician is notified and can now resume the saved TEAMATE session. Every setup and test performed by the technician and the start and end time stamps of each of these steps during the entire diagnostic, repair and replacement, and the operational checkout procedures are logged by TEAMATE into TEAMS-KB-lite. The collected data from the small TEAMS-KB-lites are combined at a maintenance site through the replication and refresh capabilities of the Oracle 8.0 and Oracle-lite databases at the site (Site TEAMS-KB is Oracle 8.0 based). TEAMS-KB also interacts with the aircraft information system database for parts prediction, scheduled maintenance actions and parts inventory management. These site TEAMS-KBs can also be combined at the manufacturer's site (Oracle 8.0 based TEAMS-KB) for data mining. The updated model parameters, such as mean-times-to-failure (MTTFs), test costs, test times, repair costs and repair times are incorporated in the models and provide feedback for enhancing TEAMATE's diagnostic strategies and/or future engineering design changes (via TEAMS). Thus, TEAMS-KB provides the glue to the entire integrated diagnostics and maintenance scenario. The complete sets of functions of the knowledge base at the maintenance and supply site are the following:

1. It provides a repository for TEAMS and TEAMS-generated models for TEAMATE.
2. The diagnostic data generated by TEAMATE and TEAMS-RT is stored in the data base.
3. The diagnostic data is used to predict spare part requirements and manage parts.

In addition, the knowledge base of models uses the new diagnostic data obtained from TEAMATE's interactive diagnostic sessions to estimate the following failure/repair parameters:

1. Mean Times to Failure (MTTFs)
2. Mean Times To Repair (MTTRs)
3. Stockage Levels
4. Re-Order Points
5. Test Times/Costs
6. Repair Times/Costs

We are in the process of expanding the scope of the knowledge base to update rectification times and rectification costs as well.

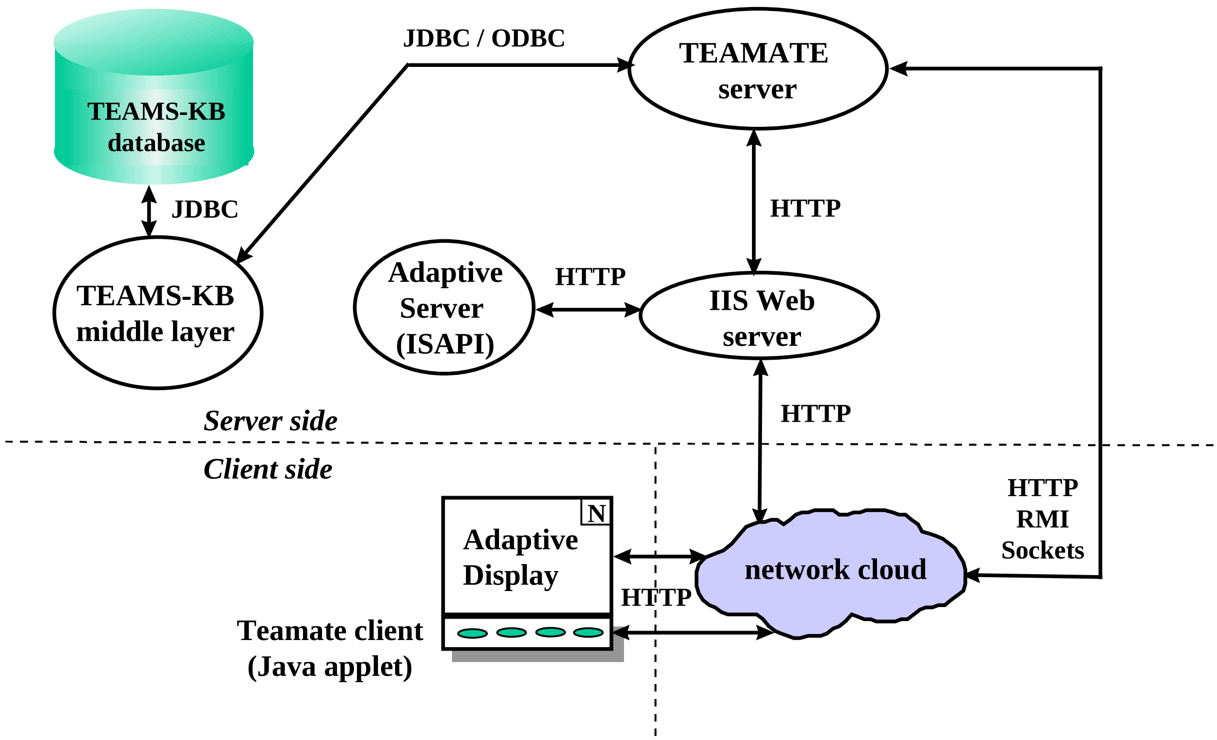


Figure 3: Communication protocols between different modules of ADAPTS

System Design and Communication Protocols

Utilization of open communication protocols, a component architecture and clean, publishable interfaces for various modules in the ADAPTS architecture are critical to its scalability and extensibility. Adopting open protocols and a component architecture with a published interface to our modules allows a plug-and-play capability with other third-party modules that also adopt those protocols and implement the interfaces. There are several open protocols that are used for communication among independent software modules. The current architecture of the TEAMATE server and client supports different protocols for communication (Fig. 3). These include Microsoft's proprietary DDE, Object Management Group's standard CORBA [7], Sun Microsystems's RMI protocol. In addition, we have recently implemented the standard Hyper Text Transfer Protocol (HTTP) and standard Sockets. Implementing these different protocols is critical to support a multitude of scenarios that can occur during deployment.

For the ADAPTS project, one of the specifications was that the ADAPTS client be a Windows application with an embedded Internet Explorer browser control and that TEAMATE client be required to operate in that environment. In addition, the entire maintenance system had to be demonstrable from a mobile computing environment, which may or may not be connected to the network. However, the same system should also be scalable enough to be deployed over the network (Intranet/Internet) with or without the presence of corporate firewalls. Corporate firewalls limit Internet communication to a limited number of well-known ports. In addition, the technology should be capable of utilizing databases other than Oracle.

Another project where we are deploying a similar technology for integrated maintenance is in the Joint Advanced Health and Usage Monitoring System (JAHUMS) program [8]. This program has a different set of requirements/specifications. For example, the client application in the JAHUMS program is not browser based. Instead, it is a Windows application with a built-in SGML viewer. In this context, TEAMATE is a server and the IETM is its client. The fact that the deployment platform for TEAMATE is a Windows95 notebook system allowed us to use a simple but robust DDE protocol to communicate between TEAMATE and the IETM. Thus, TEAMATE's flexible and adaptable architecture, that provides a consistent interface but allows different communication protocols between the server and the client, has allowed us to transparently address this case. In addition, the hardware requirements for the PEDD are strict and are considerably more stringent compared to the ADAPTS system.

Satisfying the different sets of hardware/software/network specifications/requirements for an integrated maintenance system necessarily requires the adoption of open protocols and standards compliance. Figure 3 shows the system architecture of TEAMATE, TEAMS-KB, the Adaptive Server and the communication protocols that are used in the ADAPTS implementation. The ADAPTS system has most of the processing on the server-side and the client-side was designed to include very little processing. The thin-client strategy is very effective for deployment because the client environment can be very different from one application to another. Ideally a state-less client is the best solution for operation across all the different client platforms and their various configurations. The ADAPTS system primarily focuses on being operational on the Windows environment only. The thin-client in this case is a Windows application with an Internet Explorer browser control that communicates to the servers. The client thus consists of the TEAMATE Java applet embedded in the browser control. The content for the current operation being displayed in the browser is dynamically generated as dynamic HTML and JavaScript. Thus apart from the Java applet, the client is virtually state-less. All communication between the client and the various servers is accomplished using the HTTP protocol only. This allows the client and server communication possible across any network and through corporate firewalls. As far as the TEAMATE client is concerned, communication between it and its server is attempted first with sockets, which is a very reliable and a low level protocol. If the server cannot open an arbitrary port and listen to it, i.e., there is a corporate firewall present, it tries the HTTP protocol for which the firewall has a well-known port already assigned. Although TEAMATE client server communication using RMI and CORBA is also implemented, we did not use them in the ADAPTS project because of the lack of support for the RMI protocol by the Internet Explorer. Internet Explorer also does not have a built-in ORB (unlike the Netscape Communicator browser). Hence, using CORBA would have made the TEAMATE client load significantly slower, because all the CORBA classes are required to be downloaded to the client system first. Thus, implementation of a variety of client-server communication protocols provided a greater flexibility in adapting to the deployment scenario than a monolithic single protocol implementation.

BENEFITS OF INTEGRATION AND ROI

The major benefit in deploying such an integrated maintenance system is the reduction of the overall life cycle cost of a system. This is achieved by impacting several measures of maintenance performance as follows:

a) reduction in maintenance cost including RTOKs, because of accurate fault isolation by the seamless integration of on-board monitoring (via TEAMS-RT) and ground support (via TEAMATE),

b) rapid turn around time especially in mission-critical situations. The integrated system allows much of the fault diagnosis to be performed on-board via TEAMS-RT and reduces the dependence on field and depot level maintenance. In addition, TEAMATE's diagnostic strategies reduce the troubleshooting time by a factor of 3 or more over manual troubleshooting strategies embedded in standalone IETMs.

c) ready availability of parts by using the parts inventory control algorithms of TEAMS-KB that are tied to the history of parts repair and replacement as logged by TEAMATE,

d) preventive maintenance by tracking the MTTFs and MTTRs and updating them with field data logged by TEAMATE,

e) reduction in mean-downtime by better inventory control and parts management using integrated data from multiple site TEAMS-KBs,

f) adaptive, human-centered display of test procedures and content based on the expertise level of technicians reduces human errors and results in faster and effective diagnosis,

g) Adaptation of TEAMATE test strategies to the expertise levels of technicians allows the technician to perform tests more suited to her/his capability. This, in turn, results in a greater chance of successful completion of the diagnosis process,

h) TEAMATE and the Adaptive Display mechanism are easily leveraged to form an excellent training tool for technicians with varying expertise levels.

Sikorsky Aircraft developed a detailed cost-benefit analysis and a Return On Investment (ROI) analysis for deploying an integrated maintenance system on SH-60B and CH-47D helicopters as part of the JAHUMS project [8]. This project leverages the same set of QSI products as in the ADAPTS scheme. The cost-benefits analyses were performed for the engine maintenance of these two fleets. Engine maintenance savings would include savings from:

- Reduced Inspection Time
- Reduced Mean Time To Repair
- Reduced False Removals
- Reduced Spare Part Requirements
- Reduced Unscheduled Data Collection
- Reduced Training Requirements

A conservative estimate by Sikorsky Aircraft showed that the total yearly savings from deployment of an integrated maintenance technology, just for the engine maintenance alone, would be in the range of several million dollars for a fleet of 500 for each of the two fleets. An ROI analysis for the same two fleets of 500 of these two aircraft for all the subsystems of the aircraft shows a break even period of less than half a year and a 5 year return that is more than an order of magnitude over the initial investment. In summary, they conclude that *"the approximate cost benefit analysis shows that the technology being proposed holds significant potential for cost savings, partly because of low system costs, and partly because of the potential impact for savings in highly repetitive tasks for both the SH-60B and the CH-47D fleet."*

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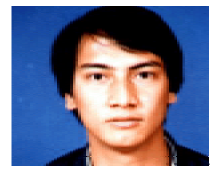
BIOGRAPHY

Sudipto Ghoshal, *is the Principal Research Engineer at Qualtech Systems, Inc. He received his B.Tech degree in Electrical Engineering from the Indian Institute of Technology, Kharagpur, India in 1989, the M.S. and Ph.D. degrees in Biomedical Engineering from the University of Connecticut, Storrs in 1991 and 1997, respectively. Prior to joining Qualtech Systems, Dr. Ghoshal was a Senior Software Engineer at Netscape Communications Corporation, Mountain View.*

Dr. Ghoshal's research interests include understanding the signal processing of neural systems and development of tools and strategies for efficient system test and diagnosis. At Qualtech Systems, he is primarily involved in developing a web based system diagnostic and training tool, TEAMATE, using Java and CORBA and is involved in standard related efforts in the areas of diagnostics. He was also the lead developer in the development of a web based Reusable Test Library software using Java and JDBC (Java Database Connectivity).



Roshan Shrestha *has been with Qualtech Systems, Inc., since 1995, where he leads the products development group. He received his B.E. in electrical engineering from Gauhati university, India in 1989, and M.S. in Electrical and Systems Engineering from the University of Connecticut in 1994. Mr. Shrestha has extensive experience in developing commercial software products for both the UNIX and Windows environment, with expertise in C, C++, and Java language. He was the chief architect of QSI's premier product, TEAMS. Currently he is leading the development work on the network-aware version of TEAMATE, which utilizes state-of-the art CORBA, and Java technologies to perform remote diagnosis using the internet.*

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Venkatesulu Malepati *is a Software Engineer at Qualtech Systems, Inc. He received a B.E in Electrical Engineering from Gulbarga University, Karnataka, India and Master of Computing (Information Technology) from the University of Western Sydney, Australia. His expertise includes analysis, design of distributed/relational and object-oriented databases.*

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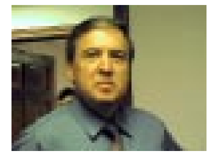
Dr. Deb's research has included the development of advanced optimization algorithms for system testability analysis and improvement, global monitoring of precision manufacturing systems, performance modeling of computer systems using queuing network theory, and multisensor multitarget tracking and data association. He has published over 20 journal and conference papers. He received the Best Technical Paper Awards at the 1990 and 1994 AUTOTEST Conferences for his work on tools for system testability analysis and multi-signal modeling.

Dr. Deb has been involved in the design and implementation of three software packages: "System Testability Analysis and Research Tool," "Testability Engineering and Maintenance System," and "PASSDAT: PASsive Sensor Data Association for Tracking." TEAMS is in use at a number of industrial sites for testability analysis of helicopter and aircraft subsystem designs. The PASSDAT software has found application in the industrial and government organizations working on large scale surveillance problems (e.g., Boeing, TRW, Naval Surface Warfare Center).

***Krishna R. Pattipati**, is the President of Qualtech Systems, Inc. He received the B.Tech degree in Electrical Engineering with highest honors from the Indian Institute of Technology, Kharagpur, in 1975, and the M.S. and Ph.D. degrees in Systems Engineering from the University of Connecticut in 1977 and 1980, respectively. From 1980 to 1986, he was at ALPHATECH, Inc., Burlington, MA, where he supervised and performed research on queuing networks, automated testing, large-scale mixed-integer optimization, human decision modeling, and multi-target tracking,. Since 1986, he has been with the University of Connecticut, where he is a Professor of Electrical and Systems Engineering. Dr. Pattipati has published over 140 articles, primarily in the application of systems theory, queuing theory and optimization techniques to large-scale systems.*

Dr. Pattipati was selected by the IEEE Systems, Man, and Cybernetics Society as the Outstanding Young Engineer of 1984, and received the Centennial Key to the Future award. He was elected a Fellow of the IEEE in 1995 for his contributions to discrete-optimization algorithms for large-scale systems and team decision-making. He won the best technical paper awards at the 1985, 1990 and 1994 IEEE AUTOTEST Conferences. Dr. Pattipati served as the Vice-Chairman for invited sessions of the IEEE International Conference on Systems, Man, and Cybernetics Conference (SMC), Boston, MA, 1989. He is currently an Associate Editor of the IEEE Transactions on SMC.



***David L. Kleinman**, is the Director of Research and Development at Qualtech Systems, Inc. Dr. Kleinman received the B.E.E. degree in Electrical Engineering from Cooper Union in 1962, the M.S.E.E. degree in Electrical Engineering from Massachusetts Institute of Technology in 1963, and the Ph.D. in Control Systems, Massachusetts Institute of Technology, 1967.*

Dr. Kleinman is internationally known for his work on manual control, human decision-making research, and computational algorithm development. He is a pioneer in the application of modern control and estimation theory to develop and validate an analytical model for describing human control and information processing performance in manned vehicle systems. In 1994, he was elected a Fellow of the IEEE. In various industrial positions and academic positions, he has led applied research projects in both manual control and automatic control. Examples include fixed-wing aircraft, helicopters and submarine control. By way of these applications and other applications, he has established credibility in applied digital control, parameter estimation, Kalman filtering, and simulation. His efforts in human decision-making have involved modeling operator performance and response characteristics in real-time multi-task sequencing and scheduling problems. His current research, which is funded through grants from the Office of Naval Research and the National Science Foundation, is in the area of multi-human decision-making in dynamic environments, and coordination in human teams. Dr. Kleinman has done extensive research in the area of team decision making within military Command and Control contexts.