



# **3D-based Advanced Machine Service Support**

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## **Declaration**

No part of the material described in this thesis has been submitted for the award of any other degree or qualification in this or any other university or college of advanced education.

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## Abstract

In the face of today's unpredictable and fluctuating global market, there have been trends in industry towards wider adoption of more advanced and flexible new generation manufacturing systems. These have brought about new challenges to manufacturing equipment builders/suppliers in respect of satisfying ever-increasing customers' requirements for such advanced manufacturing systems. To stay competitive, in addition to supplying high quality equipment, machine builders/suppliers must also be capable of providing their customers with **cost-effective, efficient and comprehensive** service support, throughout the equipment's lifecycle.

This research study has been motivated by the relatively unexplored potential of integrating 3D virtual technology with various machine service support tools/techniques to address the aforementioned challenges. The hypothesis formulated for this study is that a 3D-based virtual environment can be used as an integration platform to improve service support for new generation manufacturing systems. In order to ensure the rigour of the study, it has been initiated with a two-stage (iterative) literature review, consisting of: a preliminary review for the identification of practical problems/main issues related to the area of machine service support and in-depth reviews for the identification of research problems/questions and potential solutions. These were then followed by iterations of intensive research activities, consisting of: requirements identification, concept development, prototype implementation, testing and exploration, reflection and feedback. The process has been repeated and revised continuously until satisfactory results, required for answering the identified research problems/questions, were obtained.

The main focus of this study is exploring how a 3D-based virtual environment can be used as an integration platform for supporting a more cost-effective and comprehensive strategy for improving service support for new generation manufacturing systems. One of the main outcomes of this study is the proposal of a conceptual framework for a novel 3D-based advanced machine service support strategy and a reference architecture for a corresponding service support system, for allowing machine

builders/suppliers to: (1) provide more cost-effective remote machine maintenance support, and (2) provide more efficient and comprehensive extended service support during the equipment's life cycle. The proposed service support strategy advocates the tight integration of conventional (consisting of mainly machine monitoring, diagnostics, prognostics and maintenance action decision support) and extended (consisting of mainly machine re-configuration, upgrade and expansion support) service support functions. The proposed service support system is based on the integration of a 3D-based virtual environment with the equipment control system, a re-configurable automated service support system, coupled with a maintenance-support-tool/strategy support environment and an equipment re-configuration/upgrade/expansion support environment, in a network/Internet framework.

The basic concepts, potential benefits and limitations of the proposed strategy/system have been explored via a prototype based on a laboratory-scale test bed. The prototype consists of a set of integrated modular network-ready software tools consisting of: (1) an integrated 2D/3D visualisation and analysis module, (2) support tools library modules, (3) communication modules and (4) a set of modular and re-configurable automated data logging, maintenance and re-configuration support modules. A number of test cases based on various machine service support scenarios, have been conducted using the prototype. The experimentation has shown the potential and feasibility (technical implementation aspects) of the proposed 3D-based approach.

This research study has made an original contribution to knowledge in the field of machine service support. It has contributed a novel approach of using a 3D-based virtual environment as an integration platform for improving the capability of machine builders/suppliers in providing more cost-effective and comprehensive machine service support for complex new generation manufacturing systems. Several important findings have resulted from this work in particular with respect to how various 2D/3D visualisation environments are integrated with machine service support tools/techniques for improving service support for complex manufacturing systems. A number of aspects have also been identified for future work.

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## List of Acronyms and Abbreviations

|          |  |
|----------|--|
| 2D       | Two Dimensional  |
| 3D       | Three Dimensional  |
| 3DVMS    | 3D-based Virtual Machine System  |
| ADC      | Analogue-to-digital Converter  |
| ADD      | Alarms and Diagnostics Database  |
| ADO      | ActiveX Data Objects   |
| AGV      | Automated Guided Vehicle   |
| AI       | Artificial Intelligence  |
| AMaReSS  | Automated Maintenance and Re-configuration Support System                    |
| ANN      | Artificial Neural Network  |
| ARN      | Activity Reference Number  |
| CAD      | Computer-aided Design  |
| CBM      | Condition-based Maintenance  |
| CBR      | Case-based Reasoning   |
| CPM      | Communication Proxy Module   |
| CMMS     | Computerised Maintenance Management System                                   |
| CNC      | Computer Numerical Control   |
| CORBA    | Common Object Request Broker Architecture                                    |
| CoSDaD   | Communication/Security Data Database   |
| CoSReSM  | Control System Re-configuration Support Module                               |
| COTS     | Commercial Off-the-shelf   |
| CPM      | Communication Proxy Module   |
| DAQ      | Data Acquisition   |
| DCOM     | Distributed Component Object Model   |
| DeFRUESE | Design Feedback, Re-configuration, Upgrade and Expansion Support Environment |
| DIRESS   | Data/Information and Re-configuration Support Server                         |
| DLL      | Dynamic Link Library   |
| DM       | Diagnostics Module   |

|         |  |
|---------|--|
| DOM     | Design Out Maintenance                                       |
| DWT     | Discrete Wavelet Transform                                   |
| EAMS    | Enterprise Asset Management System                           |
| ERP     | Enterprise Resource Planning                                 |
| ES      | Expert System  |
| FFT     | Fast Fourier Transform                                       |
| FLS     | Fuzzy Logic System   |
| FTP     | File Transfer Protocol                                       |
| HAM     | Health Assessment Module                                     |
| HeSProD | Health Status and Prognostics Database                       |
| HGU     | Hydro-electric Generation Unit                               |
| HIL     | Hardware-in-the-loop   |
| HMD     | Head Mounted Display   |
| HMI     | Human-machine-interface                                      |
| HTTP    | HyperText Transport Protocol                                 |
| IEEE    | Institute of Electrical and Electronic Engineers             |
| IIS     | Internet Information Server                                  |
| IMS     | Intelligent Maintenance System                               |
| ISA     | Instrumentation, Systems, and Automation Society             |
| ISO     | International Standard Organisation                          |
| ISSE    | Integrated Service Support Environment                       |
| IVAE    | Integrated 2D/3D Visualization and Analysis Environment      |
| IVAM    | Integrated 2D/3D Visualisation and Analysis Module           |
| KD      | Knowledge Database   |
| LAN     | Local Area Network   |
| LC      | Local Client   |
| LM      | Logging Module   |
| LON     | Local Operating Network                                      |
| MaDDID  | Machine Design Data/Information Database                     |
| MaSReD  | Machine Service Records Database                             |
| MASSIVE | Machine Service Support using Innovative Virtual Engineering |

|          |   |
|----------|---|
| MDL      | Machine Data Logger   |
| MDLM     | Machine Data Logger Module                                      |
| MaDDID   | Machine Design Data/Information Database                        |
| MaSCoM   | Maintenance Support Coordinator Module                          |
| MCM      | Main Coordinator Module   |
| MDSM     | Maintenance Decision Support Module                             |
| MFC      | Microsoft Foundation Class                                      |
| MIMOSA   | Machinery Information Management Open System Alliance           |
| MM       | Monitoring Module   |
| MSM      | Maintenance Support Module                                      |
| MSSS     | Machine Service Support System                                  |
| MSuTReSM | Maintenance-support-tools Re-configuration Support Module       |
| MSuTSSEn | Maintenance-support-tools/Strategies Support Environment        |
| OMAC     | Open Modular Architecture Control                               |
| OPC      | OLE for Process Control   |
| OSA-EAI  | Open System Architecture for Enterprise Application Integration |
| PC       | Personal Computer   |
| PCI      | Peripheral Computer Interconnect                                |
| PID      | Proportional-integral-derivative                                |
| PLC      | Programmable Logic Controller                                   |
| PM       | Prognostics Module  |
| RDD      | Raw Data Database   |
| RMI      | Remote Method Invocation  |
| RMS      | Re-configurable Manufacturing System                            |
| RMSSS    | Remote Machine Service Support Server                           |
| RUESE    | Re-configuration/Upgrade/Expansion Support Environment          |
| RUL      | Remaining Useful Life   |
| SCADA    | Supervisory Control and Data Acquisition                        |
| SCARA    | Selective Compliant Assembly Robot Arm                          |
| SDS      | Smart Distributed System  |
| SMTP     | Simple Mail Transfer Protocol                                   |

## List of Acronyms and Abbreviations

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|           |  |
|-----------|--|
| SOAP      | Simple Object Access Protocol                      |
| STDE      | Support Tool Development Environment               |
| STEP      | Standard for the Exchange of Product               |
| STIM      | Smart Transducer Interface Module                  |
| SubMaSCoM | Sub-section Maintenance Support Coordinator Module |
| SuToLib   | Support Tools Libraries                            |
| TCP/IP    | Transmission Control Protocol/Internet Protocol    |
| URL       | Uniform Resource Locator                           |
| WINSOCK   | Windows Socket                                     |
| XML       | Extended Markup Language                           |



## **Chapter 1**

### **Introduction**

#### **1.1 Background**

In the face of today's unpredictable and fluctuating global market, there have been trends in industry towards wider adoption of more advanced and flexible new generation manufacturing systems such as the Re-configurable Manufacturing System (RMS) (Colleen, 2002; DeGaspari, 2002; Koren, et al., 1999) etc. These have brought about new challenges to manufacturing equipment builders/suppliers in respect of satisfying ever-increasing customers' requirements for such advanced manufacturing systems. To stay competitive, in addition to supplying high quality equipment, the machine builder/supplier must also be capable of providing their customers with cost-effective and comprehensive service support, throughout the equipment's lifecycle (Muammer, et al., 2003; Ren, et al., 2002; Wilfried and Graupner, 2002). Machine builders/suppliers need to further streamline their current maintenance support strategies to fulfil greater customers' expectations for near-zero-downtime operations. There is also a need for an efficient mechanism for facilitating continuous improvement and optimisation of equipment performance. Furthermore, the machine builder/supplier also need to provide extended service support in the form of equipment re-configuration, upgrade and expansion support. These services are required for supporting their customers (i.e. the machine user) in responding more rapidly and cost-effectively to market changes, by facilitating in-service changes to the manufacturing system to meet new production requirements. Such support is necessary due to the complexity of new generation manufacturing systems. Additionally, in the near future, machine builders/suppliers will also be required to assume more responsibilities (e.g. as a result of new legislation etc) with regard to reducing environmental impacts (Takata, et al., 2004; Tomiyama, 1999). This implies that there is a need to reduce wastage (e.g. via optimising the re-use of existing equipment) without compromising customers' satisfaction and profits.

## 1.2 Motivations

Providing the aforementioned service support for new generation manufacturing systems and simultaneously, fulfilling various requirements (e.g. legal requirements) is, however, challenging, due to the need to deal with a multiplicity of uncertainties, generally inherent in complex systems (Phillip, 2004). Typically, these classes of equipment are highly automated, custom-made mechatronics systems, requiring a complex combination of mechanical, electrical/electronic, software components/elements and advanced control schemes. In some cases, relatively new technologies (i.e. technologies not extensively tested in industrial environments) may be employed. The challenges are further intensified by myriads of other factors such as limited historical operation reference, uncertainties associated with equipment manufacturing, operating environments, input materials, usage patterns, in-service changes in the functional requirements for equipment etc (Sutherland, et al., 2003; Takata, et al., 2004).

Generally, most current research efforts in machine service support strategy focus on streamlining maintenance support functions such as machine monitoring, diagnostics, prognostics and maintenance action decision support. This is achieved via the establishment of more efficient data/information sharing platforms, for facilitating collaboration between equipment users and equipment builders/suppliers/service providers (irrespective of their geographical locations) (PROTEUS, 2004; Ren, et al., 2002; Yoichi, et al. 2003). Latterly, extensive efforts have been made towards the implementation of more autonomous/intelligent maintenance-support-tools/systems (Bo, et al., 2000; Carl, et al., 2004; Chen and Chris, 2002; Goumas, et al., 2002; Hvass and Tesar, 2004; Impact Technologies, 2005; Khanniche and Mamat, 2001; Rolf, et al., 2003; Sutherland, et al., 2003) and their integration into a remote/web-based maintenance support system (Déchamp, et al., 2004; Eckhard and Ralf, 2002; IMS, 2005; Rolf, et al., 2000; Tsz, et al., 2003).

Despite various efforts, the implementation of automated maintenance-support-tools for new generation manufacturing systems remains challenging as a result of their (both the new generation manufacturing system's and support tools') intricacy and the

need to cater for a greater degree of uncertainty. In most cases, successful implementation of such support systems/tools often requires experts (humans) to work closely with equipment. This often implies the need for frequent site visits and access to a comprehensive set of equipment current and historical operational data/information (Carl, et al., 2004; Sutherland, et al., 2003). Such approaches are generally resource consuming and inefficient. As a result, it may not always be feasible, particularly in cases involving new generation manufacturing systems, where a large quantity of data/information needs to be dealt with and where historical reference is limited. In order to reduce the need for frequent site visits, there have been several research efforts attempting to improve existing remote data acquisition and visualisation techniques (Bellamine, et al., 2002; Jiang, et al., 2003; Mile and Mehboob, 2002). However, current approaches are, generally, insufficient, in particular, for cases involving new generation manufacturing systems. Accordingly, further research is required into more effective and efficient remote data acquisition, management and visualisation strategies/tools. This is also required to further improve the efficiency of existing equipment performance feedback and assessment mechanisms.

Additionally, the need to provide extended service support cost-effectively would require a more comprehensive strategy. Such a strategy should allow the planning, concurrent execution and coordination of various extended service support activities to be performed efficiently (i.e. being able to complete a support task within the shortest possible time-scale, with a minimum number of site visits and minimum level of experts' (humans) involvement). In most current remote service support strategies, there is generally, no integration of such support functions with conventional maintenance support functions.

In short, further research is required, specifically, into how to: (1) further streamline maintenance support for new generation manufacturing systems, to more effectively leverage existing strategies/tools, (2) provide a broader range of support services cost-effectively, and (3) seamlessly integrate extended service support functions and conventional maintenance support functions. A survey of literature has also

indicated that there is relatively unexplored potential for 3D virtual technology, particularly, in respect of using it for creating a virtual integration platform for machine service support activities. The various issues/factors have served as motivations for undertaking this research study.

## **1.3 Aim and Objectives**

### **1.3.1 Aim**

The aim of this research is to **explore how a 3D-based virtual environment can be used as an integration platform to support a more cost-effective and comprehensive strategy for improving service support for new generation manufacturing systems.**

The hypothesis formulated for this research is:

A 3D-based virtual environment can be used as an integration platform to improve service support for new generation manufacturing systems.

The main research questions identified are:

- (1) To what degree a 3D-based virtual environment is effective, as a virtual platform for the integration of extended service support functions (i.e. re-configuration/upgrade/expansion support) and maintenance support functions?**
- (2) What are the challenges and limitations of the approach? What are the available opportunities for overcoming the challenges and limitations (if there is any)?**
- (3) How a 3D-based virtual environment can be used to integrate various existing maintenance support strategies/tools for streamlining current maintenance support for new generation manufacturing systems?**
- (4) How a 3D-based virtual environment can be used to support efficient extended service support functions for new generation manufacturing systems?**
- (5) How a 3D-based virtual environment can be used to seamlessly integrate extended service support functions and maintenance support functions?**

### 1.3.2 Objectives

The objectives of this research are:

- (1) Identification of requirements for a cost-effective and comprehensive machine service support strategy/system, for new generation manufacturing systems.**
- (2) Formulation of a conceptual framework for a machine service support strategy for new generation manufacturing systems, based on a 3D-based virtual environment, to seamlessly integrate extended service support functions and conventional maintenance support functions.**
- (3) Formulation of a reference architecture for a corresponding machine service support system (for supporting the strategy in (2)).**
- (4) Design and development of a prototype for the experimentation, demonstration and evaluation of the main concepts of the proposed strategy/system.**

### 1.4 Research Contributions

- (1) This research study has contributed a novel approach of using a 3D-based virtual environment as an integration platform for improving the capability of machine builders/suppliers in providing more cost-effective and comprehensive machine service support for new generation manufacturing systems. It has contributed to a number of key findings (See section 8.2 for details.). The outcomes of the study support the hypothesis that a 3D-based virtual environment can be used as an integration platform to improve service support for new generation manufacturing systems.**
- (2) A conceptual framework for a novel 3D-based advanced remote service support strategy and a corresponding service support system for new generation manufacturing systems has been formulated. It suggests the implementation of a systematic and integrated strategy to support the machine builder/supplier in the shift from the conventional ‘product-based business model’ to the more sustainable ‘service-based business model’ (Takata, et al., 2004). This has resulted in a number of advances in remote machine support strategies as follows:**

- (a) Integration of remote support functions for supporting the development, testing, assessment and installation/re-configuration/upgrade of automated/intelligent maintenance-support-tools, to allow the maintenance-support-tools to be leveraged more cost-effectively.
- (b) Integration of a remote design feedback and control system re-configuration support mechanism for facilitating continuous improvement and optimisation of new generation manufacturing systems during their in service life. The proposed mechanism is intended for facilitating not just equipment performance improvement and optimisation, but also providing an efficient mechanism for supporting long-term equipment design improvement and optimization for removing design deficiencies/faults, eradicating/minimising equipment maintenance requirements and improving equipment service-ability, in addition to improvement in terms of functionality and performance.
- (c) Integration of extended service support functions for supporting in-service re-configuration/upgrade/expansion for new generation manufacturing systems.

Furthermore, the research has advanced the capabilities of remote maintenance support systems for supporting the proposed service support strategy for new generation manufacturing systems as follows:

- (a) Integration of a refined 3D-based virtual platform/environment (See (3) below.) for improving remote visualisation of complex new generation manufacturing systems. It provides an environment for supporting remote maintenance support and for facilitating the continuous improvement and optimisation of equipment during its in service life (for both equipment performance improvement and, long-term service-ability and maintainability improvement, in addition to improvement in terms of equipment functionality and performance).
- (b) Integration of a maintenance-support-tool/strategy support environment with the 3D-based virtual platform/environment for supporting the

development, testing, assessment and installation/re-configuration/upgrade of automated/intelligent maintenance-support-tools.

- (c) Integration of a re-configuration/upgrade/expansion support environment with the 3D-based virtual platform/environment for supporting in-service re-configuration/upgrade/expansion of complex new generation manufacturing systems.
  - (d) Integration of a re-configurable maintenance service support system (embedded in the machine system), consisting of a set of automated/partially-automated maintenance support modules, a re-configuration support system for supporting remote re-configuration/upgrade of maintenance support modules and a control system re-configuration support system.
- (3) This research has informed the refinements of the concepts of a 3D-based virtual platform for improving remote access, visualisation and re-use of data/information (design, operational and maintenance-related) of complex new generation manufacturing systems. It was observed that the effectiveness of a remote maintenance tool could be improved via the integration of 3D-based visualisation tools and other visualisation tools/techniques (e.g. 2D-based visualisation tools/techniques, video based tools/techniques etc), for creating an **integrated visualisation environment** consisting of multiple inter-linked 2D/3D visualisation environments. In the proposed system, traditional approaches have been refined to allow it to be used for visualising a mechatronics system from different perspectives (e.g. the mechanical/geometric aspect, electrical/electronics aspect, control system/scheme (both the software or hardware aspect) etc). 'Inter-link' is set up in such a way that each visualisation environment consists of virtual objects (each of which is associated with a particular component of a mechatronics system), which are interactively linked with the corresponding/closely related virtual objects in other visualisation environments (See sub-section 5.3.3.2 for details.).
- (4) A set of requirements for a more cost-effective and comprehensive advanced machine service support strategy/system for new generation manufacturing

systems has been identified. The focus of the requirements specification is on answering the need for: (1) streamlining conventional maintenance support functions, and (2) extending the range of conventional maintenance support services, in such a way to allow for more comprehensive life cycle support for new generation manufacturing systems.

- (5) A prototype based on the proposed framework has been implemented to demonstrate and explore the main concepts of the proposed strategy/system. It consists of a set of integrated modular network-ready software tools consisting of: (1) an integrated 2D/3D visualisation and analysis module, (2) support tools library modules, (3) communication modules and (4) a set of modular and re-configurable data logging, automated maintenance and re-configuration support modules. A number of test cases based on various machine service support scenarios, have been conducted using the prototype. Whilst the prototype system formulated is rudimentary in terms of functionality, it has shown the potential of how a 3D-based virtual environment can be used to provide a 'virtual integration platform', for facilitating the embodiment and coordination of various service support functions (both conventional and extended in nature).

## 1.5 Scope of the Research

The scope of this research study has been delimited to the following:

- (1) This research is focused on exploring how a 3D-based virtual environment can be used as an integration platform for **improving the capability of machine builders/suppliers** in providing more cost-effective and comprehensive machine service support throughout the equipment's life cycle, for facilitating/supporting the shift from the conventional **product-based business model** to the more sustainable **service-based business model** (Takata, et al., 2004). Note that this research study is not an attempt to explore the use of 3D virtual technology for improving maintenance management strategies/tools used by the machine user. The range of support services considered in this study includes the following: (1) conventional maintenance support (fault detection, diagnostics, prognostics and maintenance decision support) and (2) extended service support (re-configuration,



upgrade and expansion support) (See section 1.6 for the definitions of the terms ‘maintenance support’ and ‘extended service support’.).

- (2) Detailed research into the individual strategies/technologies/techniques/tools required for remote service support is beyond the scope of this research. Instead, this work is focused on leveraging and integrating the various elements into a more coherent framework (based on 3D virtual technology as the integration platform), for improving existing remote service support strategies for new generation manufacturing systems. The various elements may include the following: (1) maintenance management strategies/policies (such as Reliability-centred Maintenance etc), (2) maintenance technical approaches (such as Corrective Maintenance, Schedule-based Preventive Maintenance, Condition-based Maintenance etc), (3) maintenance support techniques/tools (such as automated/intelligent diagnostic and prognostic tools/techniques etc), (4) communication and information technologies (such as various network/ Internet technologies etc), (5) visualisation technologies (such as remote/web-based video, 3D graphic technologies etc), (6) digital signal processing techniques (such as wavelet etc), and (7) data acquisition and sensor technologies (such as smart sensors etc).
- (3) The research utilises a laboratory-scale test bed, consisting of a SCARA robot and a flexible conveyor system. Note that there are two other devices in the test bed: a gantry robot and an Automated Guided Vehicle (AGV), which do not feature in this study.

## 1.6 Research Approach

The adopted approach consists of the following main steps/activities: (1) identification of practical problems (via preliminary literature reviews), (2) identification of research problems/potential solutions (via in-depth literature reviews), (3) requirements identification, (4) concept development, (5) concept implementation, (6) testing and exploration, (7) reflection and feedback, and (8) documentation/reporting findings and identification of directions for future research and development. Figure 1.1 depicts the process flow of the various activities. Note that, in practice, the process is inherently iterative, as illustrated.

The research study was initiated with a two-stage literature review (after the selection of a general research area – machine service support), consisting of: preliminary and in-depth reviews. The preliminary review was conducted for the identification of (general) practical problems/main issues related to the area of machine service support. It focused on the following areas: general background information related to machine service/maintenance, existing machine service/maintenance support strategies (mainly commercial), recent developments and research efforts in various relevant areas such as emerging standards, emerging/new strategies/techniques, technological advancements etc.

The second stage of the literature review – in-depth review, was conducted for the identification of more specific research problems/questions, generally, after the completion of the preliminary review. It also served the purpose of identifying potential solutions for the identified/selected practical problems, which may have been researched previously (but have not been sufficiently/extensively researched) or those employed successfully in other areas. In this research, the focus has been on the applications of 3D virtual technology in machine service support and various other related areas. Note that, this step has been conducted continuously and in parallel with the other steps (from step 3 to 7), throughout the period of this research study. This was necessary to ensure that potential developments in related areas could be continuously fed back to the other

activities throughout the research period. Note that in practice, the two-stage review is necessarily iterative in nature.

The third step is requirements identification, conducted to identify a set of requirements for a desired solution to answer the identified/selected research problems/questions (and eventually, to contribute to solving all or parts of the identified/selected practical problems). This step served to provide a set of reference criteria for the testing and exploration process (step 6). In the fourth step – concept development, one or more conceptual frameworks (for both process models and the corresponding toolsets) were formulated based on the sets of requirements specified in the previous step.

In the fifth and sixth steps – implementation, testing and exploration, one or more of the formulated frameworks were implemented (in the form of software and hardware prototypes) which involved the development, experimentation and exploration of one or more prototypes for demonstrating and exploring the potential of the formulated conceptual frameworks. Due to various resource constraints, it has only been practical (within the three-year time scale of this research study) for the testing and exploration process to be based on a laboratory test bed.

This was followed by step 7 – reflection and feedback, where the problems/limitations and potential refinements for one or more of the formulated conceptual frameworks and developed prototypes were identified. The step also provided inputs for the selection of one or more optimum conceptual frameworks (or elimination of infeasible concepts). The identified potential refinements, together with any additional information from the literature review (which was conducted in parallel) were fed back for the revision of one or more of the selected conceptual frameworks, which may require the repetition/revision of one or more of the previous steps, as illustrated in figure 1.1. These cycles were interrupted/stopped once satisfactory results (based on the specified sets of requirements as the criteria), for answering the identified research problems/questions, were obtained.

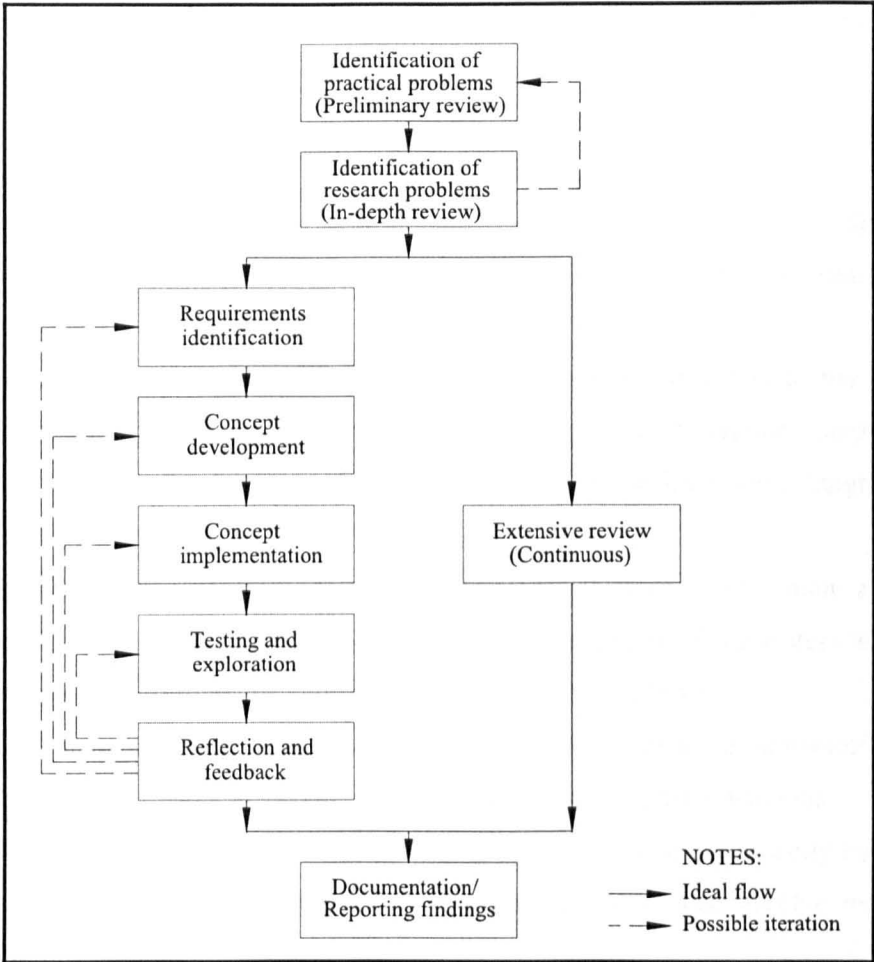


Fig. 1.1 Adopted research approach

In the last step, findings were documented and reported. In addition, a number of deficiencies and potential extensions for this study have also been identified for future research and development.

**1.7 Definitions of Terms**

This section provides definitions for some technical terms used in this thesis. Note that the definitions used here may differ from those of the same/similar terms used in other literature.

**3D virtual environment** refers to *a hypothetical three-dimensional visual world created by a computer* (Virtual Reality, 2005). It should, however, be noted that in this thesis, it refers only to the non-immersive version.

**3D-based virtual environment** refers to a computer-generated environment, which is based on one or more 3D virtual environments (See also the definition for **3D virtual environment**.) and other non-3D virtual environments (such as a virtual instrument).

**Extended machine service support/extended service support** refers to the extended range of support services, which includes equipment re-configuration, upgrade, and expansion support. To avoid confusion, the terms 're-configuration', 'upgrade' and 'expansion' are defined as follows:

- Equipment re-configuration involves structural changes to equipment at various levels such as the component level, machine level and machine system level. The process may involve the addition or removal of components.
- Equipment upgrade involves the replacement of existing software/hardware components (again, at various levels) with updated/upgraded versions.
- Equipment Expansion involves extending existing equipment capacity by addition of new components or equipment. The process may also involve removal of components.

**Failures** refer to *the lack of ability of a component, equipment, sub system, or system to perform its intended functions as designed. Failures may be the result of one or many faults* (Wikipedia, 2005a).

**Faults** refer to *any significant deviations from nominal system behavior* (Hvass and Tesar, 2004) (See also the definition of **failures**.). **Abrupt faults** are *faults that occur very quickly*. **Insipient faults** refer to *faults that are due to wear, operation-dependent and are most likely governed by non-linear constitutive laws* (Hvass and Tesar, 2004).

**Functional life** refers to the period of time during which a product is able to provide the required functions to customers, i.e. to satisfy the needs of customers (Takata, et al. 2004). In order to maintain/prolong the **functional life** of a product, changes would need to be made to the original design of the product if it was not originally designed for providing the required new functions.

**Machine maintenance support/maintenance support** refers to the conventional service support, which includes all functions performed to maintain the physical life of equipment. The support activities include fault monitoring/detection, diagnostics, prognostics, maintenance decision support and execution of maintenance services.

**Maintainability and serviceability** refers to *the ease and speed with which any maintenance activity can be carried out on an item of equipment* (Sandy, 2002).

**New generation manufacturing systems** refer to the emerging classes of manufacturing systems, designed to answer the need in industry for manufacturing systems with high responsiveness to fluctuating market changes, such as the Re-configurable Manufacturing System (RMS) (Colleen, 2002; DeGaspari, 2002; Koren, et al., 1999) etc. Note however that the term does not refer specifically to the RMS. Instead, it refers, generally, to any manufacturing systems with the following characteristics: highly automated, custom-made mechatronics systems and designed with built-in flexibility. Flexibility in this case refers to the ability to be rapidly and cost-effectively adjusted in terms of the equipment mechanical structure at certain level(s) (such as the machine level and machine system level etc) and/or in terms of the output capacity.

**Physical life** refers to the period of time during which a product remains in conditions sufficient for it to provide the functions it was designed for (Takata, et al. 2004). In order to maintain/prolong the **physical life** of a product, changes in the form of re-conditioning and/or replacement/upgrade of parts of a product may be required.

## 1.8 Thesis Outline

This thesis is organised into 8 chapters. The following paragraphs present the outlines of the remaining chapters of this thesis.

**Chapter 2** presents an overview of current research and development in the area of machine service support. The review is focused on the following areas: (1) machine maintenance approaches, (2) machine service support strategies, (3) emerging standards for maintenance support systems, and (4) sensors and data acquisition technologies. The identified limitations (specifically, in relation to remote service support for new generation manufacturing systems) of existing approaches/systems, and improvement opportunities, derived from the review are presented in the discussion sections with conclusions identified.

**Chapter 3** presents an overview of the applications of 3D virtual technology in current machine service support. The review is focused on the following aspects: (1) maintenance operation design and planning, (2) maintenance operation training, (3) onsite maintenance support and (4) remote monitoring and collaborative maintenance. A review of an industry-based Swedish project – MASSIVE, which has served as a motivation for extending this research study, is also presented in this chapter. The applications of 3D virtual technology in the areas described in (4) above are particularly relevant to this research study.

**Chapter 4** presents a detailed description of a proposed 3D-based advanced machine service support strategy for new generation manufacturing systems. It first presents a brief outline of the requirements identified for the proposed strategy. A later section presents a conceptual framework for the proposed strategy. This is followed by the discussion of various service support scenarios, for illustrating the coordination and interactions between the component activities of the proposed strategy.

**Chapter 5** presents a detailed description of a proposed 3D-based integrated remote machine service support system for supporting the strategy proposed in chapter 4.

Similar to chapter 4, this chapter first presents a brief discussion of the requirements identified for the proposed support system, followed by details of a reference architecture. It also presents a detailed discussion of how the proposed system can be used to support the proposed service support strategy (as presented in chapter 4).

**Chapter 6** presents details of a test bed and the implementation of a prototype for demonstrating the main concepts of the proposed strategy/system.

**Chapter 7** presents a discussion of five main test cases used to demonstrate and explore the feasibility and effectiveness of the proposed service support strategy/system based on the various scenarios presented in chapter 4 and 5.

**Chapter 8** presents the thesis summary, findings, contributions, conclusions and recommendations for future work.



## **Chapter 2**

# **Review of Current Developments in Machine Service Support**

## **2.1 Introduction**

This chapter presents an overview of current developments in the area of machine service support. The review focuses on the developments in the following five main areas: (1) machine maintenance approaches/techniques (technical), presented in section 2.2, (2) machine service support strategies, presented in section 2.3, (3) emerging standards for maintenance support systems, presented in section 2.4 and (4) sensors and data acquisition technologies, presented in section 2.5. The last section (2.6) summarises the findings of the literature survey.

## **2.2 Machine Maintenance Approaches/Techniques**

### **2.2.1 Introduction**

This section (2.2) is intended to provide the reader with some background information about various existing machine maintenance approaches/techniques. First, sub-section 2.2.2 and 2.2.3 present two ‘traditional’ approaches in machine maintenance – Reactive/Corrective Maintenance and Schedule-based Preventive Maintenance. Next, sub-section 2.2.4 presents an approach, which is currently considered as the most prominent approach in machine maintenance – Condition-based Maintenance (CBM). Finally, sub-section 2.2.5 and 2.2.6 present two additional concepts, which complement the other approaches – Design Out Maintenance (DOM) and Self-maintenance. Note that it has been found that a number of variants derived from one or more of the above approaches have been reported in literature. For a discussion and comparison between various approaches, see Davies, chapter 21, (Davies, 1998), Sandy (Sandy, 2002), Shikari (Shikari, 2004) and Waeyenbergh (Waeyenbergh and Pintelon, 2002).

### **2.2.2 Reactive/Corrective Maintenance**

Reactive/Corrective Maintenance is an approach where maintenance operations are carried out in response to equipment failures (either functional or physical failures), in

order to restore the functions of equipment. Even though this approach is considered to be inefficient in most cases, it is, however, inevitable in some cases. In other cases, it is the preferred approach. The approach is generally inevitable in cases involving components with unpredictable/abrupt failure modes (i.e. there is no way of observing the degradation trend, degradation time is too short or it is infeasible (not cost-effective) to observe the degradation trend) such as on/off type components (Hosseini, 2005). The approach is typically adopted for the maintenance of components/equipment systems, which are either non-critical, low cost or where it is acceptable for a component to operate until it fails (e.g. the failure would not cause any/serious secondary failures and that the subsequent maintenance operations could be performed cost-effectively, without negatively/significantly impacting the normal operations of equipment) (Waeyenbergh and Pintelon, 2002).

### **2.2.3 Schedule-based Preventive Maintenance**

Schedule-based Preventive Maintenance is an approach where maintenance operations are performed based on a schedule, which typically is either time-based or distance-based. Time-based Preventive Maintenance is based on a pre-set time schedule such as in terms of months, hours of operations etc. Distance-based Preventive Maintenance is based on a pre-set operating distance such as in terms of distance of travel, number of cycles etc. In general, Distance-based Preventive Maintenance is considered to be more optimum than the Time-based approach (Holden, 2003). It is typically adopted for tackling age-related deterioration (Waeyenbergh and Pintelon, 2002). This approach can be effective (but not necessarily cost-effective) for equipment with constant (or with a narrow range of) operating loads and conditions, and provided maintenance operations are performed correctly (i.e. no source of faults is introduced unintentionally into the equipment system during the maintenance operations). Unfortunately, in most cases, the implementation is not optimum where maintenance operations are often carried out unnecessarily. Some of the main criticisms against the approach are (Takata, et al. 2004; Waeyenbergh and Pintelon, 2002): (1) unnecessary maintenance operations cause disruptions to normal operations, (2) ineffectiveness of the approach due to the large number of uncertainties inherent in most complex equipment

systems, (3) in most cases, the chances of improper maintenance operations remain high, resulting in inevitable introduction of sources of faults into the equipment systems during maintenance operations and (4) pre-mature removal/replacement of good components, unnecessarily.

#### **2.2.4 Condition-based Maintenance**

Condition-based Maintenance (CBM) is an approach where maintenance operations are performed only when necessary in order to prevent equipment breakdowns, based on the conditions of equipment. It is based on the idea that the *majorities of failures do not occur instantaneously but develop over a period of time* (Waeyenbergh and Pintelon, 2002). It requires that there must be a feasible way of observing the degradation trends of components/equipment. This approach is currently the most widely advocated maintenance approach (OSA-CBM, 2003). Due to the high implementation costs of the approach and the need for experts, there have been various research efforts focusing on automating some of industrial-proven CBM-based techniques (See sub-section 2.3.3 for examples.). For a comprehensive discussion of condition monitoring techniques, refer to Davies (Davies, 1998).

#### **2.2.5 Design Out Maintenance**

Design Out Maintenance (DOM) focuses on improving the design of equipment for the purpose of: minimizing maintenance requirements or eliminating specific maintenance requirements or facilitating maintenance operations (i.e. improving the maintainability/serviceability of equipment). It is typically adopted for tackling recurring equipment problems (Waeyenbergh and Pintelon, 2002), which involve high maintenance/service costs (Shikari, 2004). According to the concept of DOM, the problems may be alleviated by modifying the original design of equipment (or by completely re-design parts of equipment) in such a way that costly failure modes could be minimized or eliminated. For the approach to be effective (and to avoid costly errors), extensive studies are typically conducted, in the initial phase, into the effects of component/equipment changes on the overall system before embarking on the equipment re-design process (Waeyenbergh and Pintelon, 2002).

### 2.2.6 Self-maintenance

Self-maintenance is an approach, where an equipment system is designed to automatically maintain/recover its functions after a fault (Umoda and Shimomura, 1994). In general, there are three approaches to achieving self-maintenance (Umoda and Shimomura, 1994): (1) *part redundancy*, (2) *control* and (3) *functional redundancy*. The *part redundancy* type strategy is a traditional approach where a critical primary component is designed to have a backup component (i.e. a redundant component), which would take over the functions of the primary component in case of faults. The strategy is, generally, justifiable only for cases involving highly critical components/equipment. It also requires that reliable and feasible automated fault detection and diagnostic strategies to be available. The main disadvantages of this strategy are (Umoda and Shimomura, 1994): high costs, additional weight, unnecessary performance penalties and greater complexity. Accordingly, the *control* type and *functional redundancy* type strategies were introduced (Umoda and Shimomura, 1994). The *control* type strategy is based on adjusting/re-configuring equipment control parameters in case of faults, in order to maintain its functions (at lower performance levels) for a prolonged period (ideally, until maintenance operations could be performed). The third type – *functional redundancy* type strategy is based on using a component in a way slightly different from what it was originally designed for, to replace a faulty component (i.e. to perform functions on behalf of the faulty component, temporarily) (Umoda and Shimomura, 1994). Typically, the *control* and *functional redundancy* type strategies are used in conjunction, in the form of a two-stage strategy (For more details on this, see Umoda and Shimomura, 1994).

### 2.2.7 Discussion

Among the various concepts presented above, the Condition-based Maintenance (CBM) and Design Out Maintenance (DOM) approaches are particularly relevant to the service support for new generation manufacturing systems. CBM-based techniques, in general, have been used extensively in existing machine maintenance support strategies/systems, in particular, for large constant speed rotary machinery typically used in high value plants such as power plants, chemical plants, huge ships etc. Latterly,

various research and development efforts have been made towards automating some of industrial-proven CBM-based techniques. See section 2.3.3 for more details about current developments in the area of automated/intelligent CBM-based support techniques. It should also be noted that since the CBM is concerned mainly with *insipient faults*, it is generally, not applicable to cases involving *abrupt faults* (Hvass and Tesar, 2004). In such cases (i.e. those involving abrupt faults), it would not be feasible to either automate existing CBM-based techniques or to use CBM-based techniques at all. Typically, Reactive/Corrective and Scheduled-based Preventive Maintenance approaches are inevitable in these cases. The above situations may be improved by adopting the DOM concept (e.g. by re-design selected components in such a way that the requirements for certain maintenance procedures could either be minimized or eliminated etc). To more effectively take advantage of DOM, a service support strategy/system should include an efficient mechanism for facilitating the acquisition, storage, transfer, visualization, analysis and re-use of equipment operational data/information. Additionally, in order to take advantage of the concept of Self-maintenance, further research into various issues such as the need to improve existing intelligent diagnostic and prognostic techniques, is necessary before they could be fully exploited for maintenance support for new generation manufacturing systems.

## **2.3 Machine Service Support Strategies**

### **2.3.1 Introduction**

This section (2.3) presents an overview of current advances in machine service support strategies. The review is intended to identify the current achievements, limitations and improvement opportunities for existing service support strategies, particularly, in relation to improving service support for new generation manufacturing systems. First, sub-section 2.3.2 presents a brief review of various currently available commercial machine service support solutions. Sub-section 2.3.3 then presents some of the research and development efforts attempting to improve existing machine service support strategies/systems. Next, sub-section 2.3.4 presents a recent concept in machine service support – lifecycle support. Note that it is not the intent of this survey to provide a comprehensive review of current achievements in the area of machine service support due to large number of research efforts currently underway in this area. Instead, it is delimited to some of the prominent techniques, targeting mainly manufacturing equipment.

### **2.3.2 Commercial Maintenance Support Solutions**

In response to ever increasing customer demands for near zero downtime operations, various commercial remote machine service support solutions have been introduced. Examples of machine suppliers/service providers providing such solutions are: GE Fanuc (GE Fanuc, 2005a), Rockwell Automation (Rockwell, 2004) and SKF (SKF, 2005). In general, various solutions have been implemented successfully for remote condition monitoring of typical plant equipment such as electric motors (driving fans, pumps etc), compressors, turbines, CNC machines etc. Typically, the solutions combine web-based technologies and various condition-based maintenance techniques such as vibration monitoring, wear particles/oil debris monitoring, thermal monitoring etc. The support tools allow remote experts to remotely acquire, visualize and analyse equipment operational data via a web browser. Figure 2.1 shows a view of an example of a web-based remote monitoring tool from SKF (SKF, 2005) called the SKF Machine Analyst/Remote Access. Some support tools allow remote experts to interact directly with the equipment control system or diagnostic sub-system embedded in the equipment

system, allowing remote experts to perform diagnostics/troubleshooting remotely. An example of such a system is the Open Factory CNC solution from GE Fanuc Automation (GE Fanuc, 2005b), which has been integrated with remote-access software such as the Symantec's PAnywhere (Symantec, 2004). The support system allows remote experts to access most/some of the built-in troubleshooting functions of a CNC machine. In general, these tools have been used successfully by some machine builders/suppliers in improving the cost-effectiveness and efficiency of their machine service support strategies.

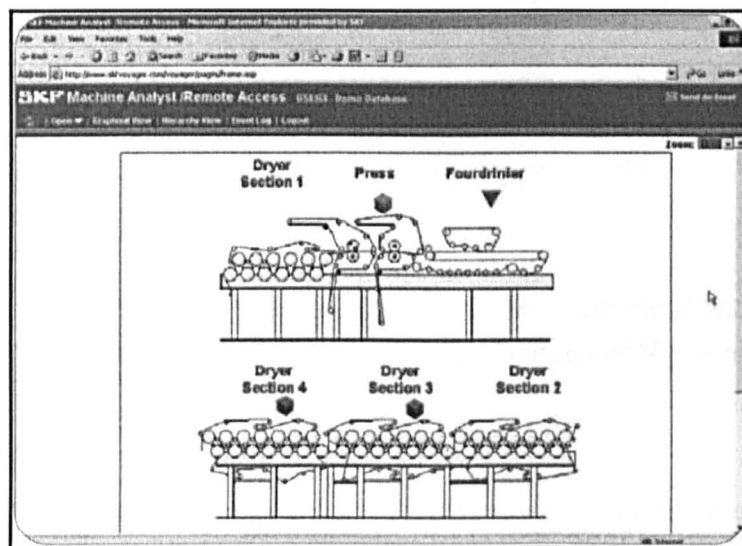


Fig. 2.1 Web-based remote monitoring (Courtesy of SKF, 2005)

In addition, there have also been various successful industry-based test cases/pilot projects, aimed at evaluating the feasibility and effectiveness of remote machine service support strategies. Examples of such test cases have been reported by: Vigliermo (Vigliermo, 2003) and Coax (Coax, 2003). Vigliermo described a web-based remote service support system for supporting CNC machines. Figure 2.2 shows a view of the web-based monitoring interface for CNC machines. Coax described a similar web-based service support system for supporting textile machines. The various test cases have demonstrated the feasibility of remote machine service support strategies. In general, the test cases also indicated that the implementation of such support strategies received

positive feedback from most customers (Vigliermo, 2003). This may be attributed to various benefits gained such as reduced equipment downtime, lower service costs with improved service quality and reduced repair/troubleshooting time.

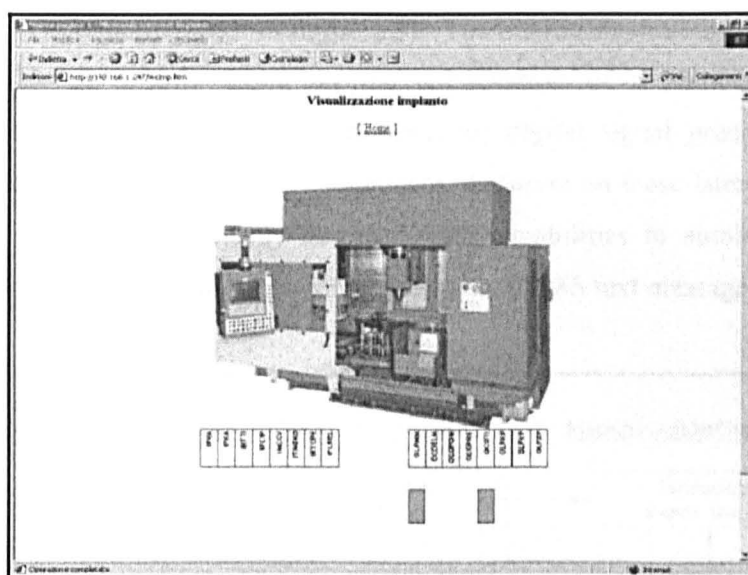


Fig. 2.2 Web-based CNC machine monitoring (Courtesy of Vigliermo, 2003)

### 2.3.3 Current Research Efforts

There have also been (and ongoing) extensive research efforts aimed at improving existing machine service support strategies/systems. In general, the various proposed strategies/systems focus on streamlining machine service support activities via the establishment of closer collaboration/partnerships between equipment users and equipment suppliers/service providers, by taking advantage of existing information and communication technologies.

Various web-based remote maintenance support strategies/systems have been proposed (Déchamp, et al., 2004; Eckhard and Ralf, 2002; IMS, 2005; Rolf, et al., 2000; Tsz, et al., 2003). Figure 2.3 shows a typical activity flow of conventional maintenance support strategies and figure 2.4 depicts a typical (simplified) configuration of such support systems. In general, most proposed systems are based on the integration of data acquisition, distributed intelligent/automated maintenance support, network/Internet and



web-based visualization technologies. The web-based visualization is typically a 2D graphics interface (Similar to that shown in figure 2.1/2.2.). It provides a remote user interface, which allows maintenance personnel/remote experts to access and visualize equipment operational data and analysis outputs of automated maintenance-support-modules (the ‘Analysis Modules’ in figure 2.3). The intelligent/automated maintenance-support-modules are mostly based on the combination of a number of software components performing various functions such as: digital signal processing, feature extraction, classification, diagnostics, prognostics etc (more on these later). In addition, the proposed systems are typically designed with capabilities to automatically alert/remind machine experts via various other means such as SMS text messages, emails etc.

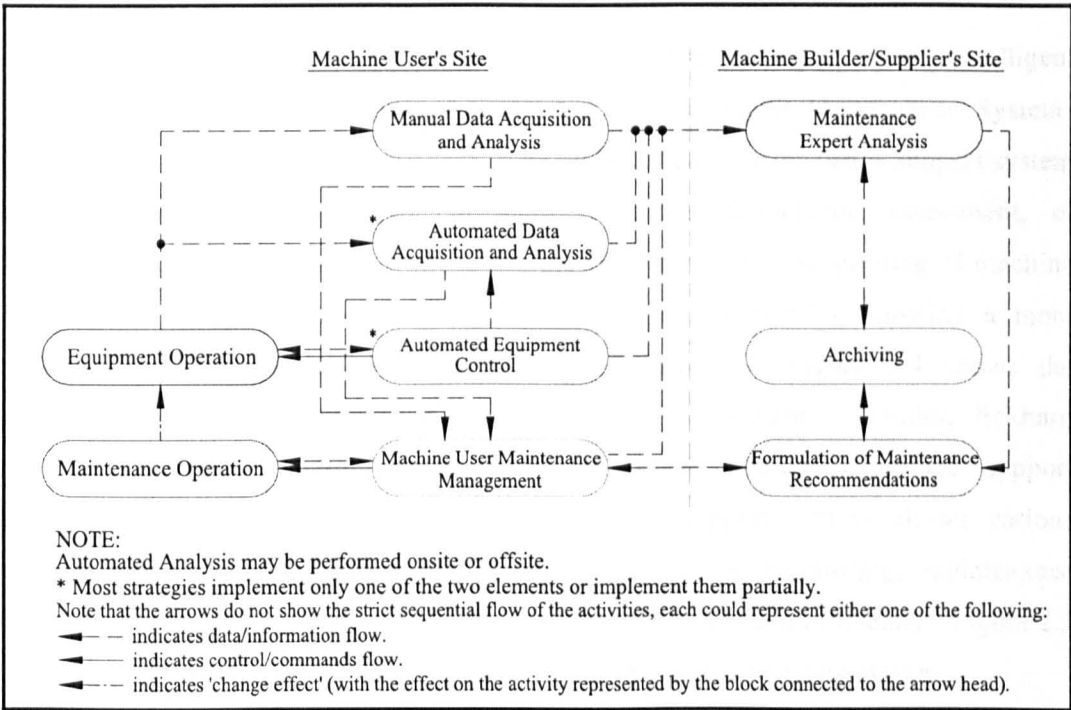


Fig. 2.3 Typical activity flow of conventional remote maintenance support strategies

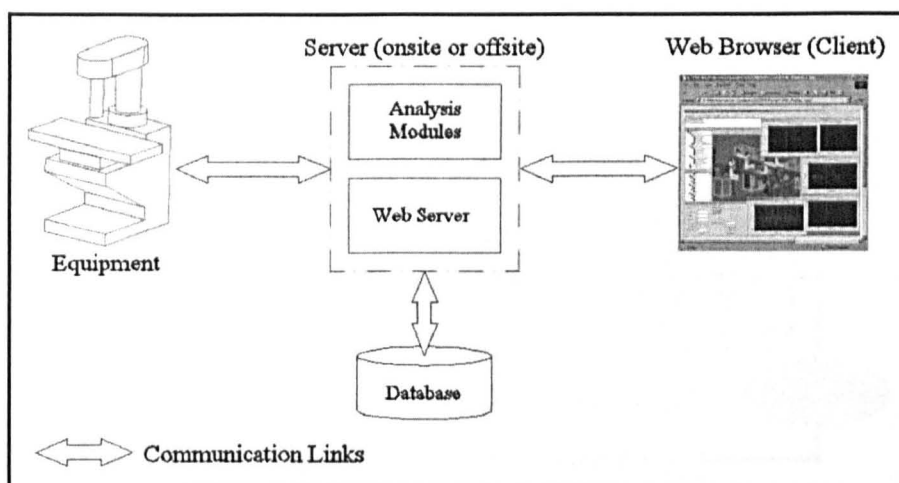


Fig. 2.4 A typical configuration of web-based remote maintenance support systems

One of the prominent examples of such implementation is the Intelligent Maintenance System (IMS, 2005) developed at the Intelligent Maintenance Systems Center (IMS, 2005). The proposed IMS is an Internet-based maintenance support system integrated with components for intelligent machine degradation assessment, e-prognostics and e-diagnostics. It facilitates the real time remote monitoring of machine performance and prediction of future trends (degradation trends), allowing a more effective preventive maintenance strategy to be realised. Figure 2.4 shows the configuration of the intelligent e-maintenance support system. Besides, Eckhard (Eckhard and Ralf, 2002) described an integrated web-based service support system/strategy for CNC machines. The proposed support system allows various maintenance support services such as remote condition monitoring, maintenance assistance, e-training etc to be provided more cost-effectively and efficiently. Figure 2.5 shows the configuration of the web-based remote condition monitoring system.

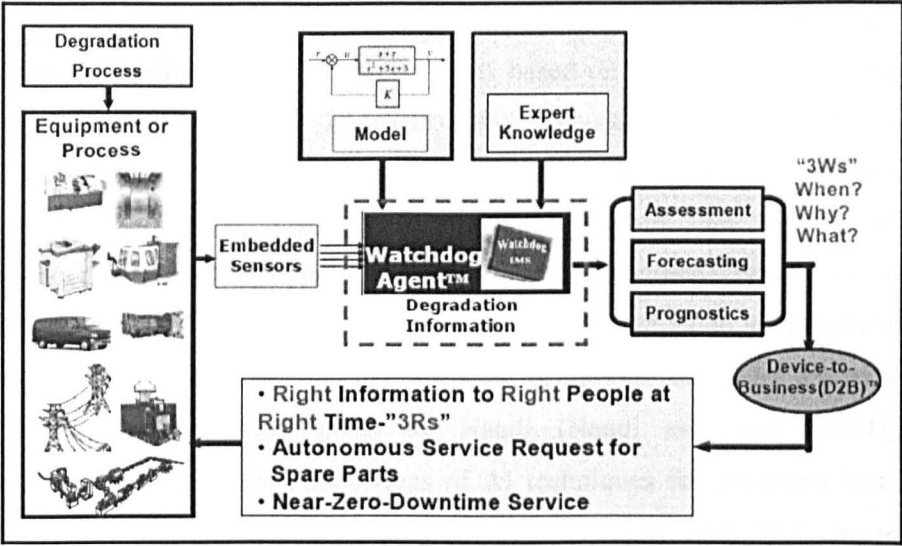


Fig. 2.5 Intelligent maintenance system (Courtesy of IMS, 2005)

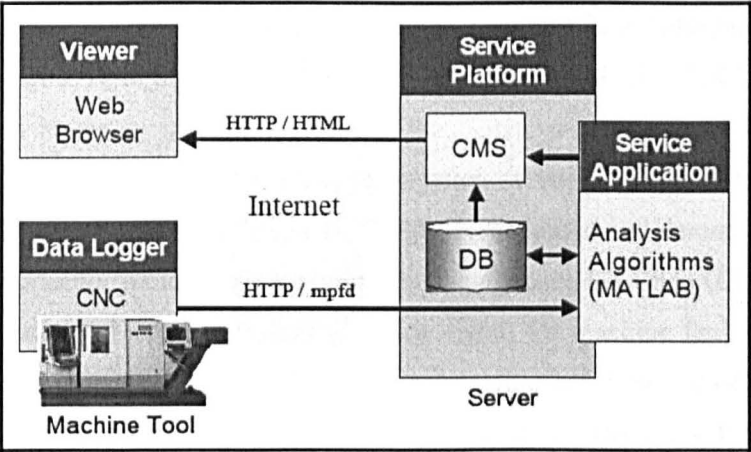


Fig. 2.6 A web-based remote condition monitoring system (Courtesy of Eckhard and Ralf, 2002)

In the area of automated/intelligent maintenance support, most recent research efforts have been focusing on automating some of industry-proven CBM techniques such as vibration-based and wear particle-based techniques. The tools typically make use of various signal processing techniques (such as the Fast Fourier Transform (FFT), wavelet transforms (e.g. Discrete Wavelet Transform (DWT)), statistical techniques etc) and artificial intelligence (AI) technologies (such as expert systems (ESs), artificial neural

networks (ANNs), fuzzy logic systems (FLSs) etc). Apart from AI-based techniques, there have also been extensive research efforts based on model-based techniques (first principles models) techniques (Agustin, 2000; Hvass and Tesar, 2004; Impact Technologies, 2005 etc). Model-based techniques are generally more complex and thus more costly to implement (Carl, et al., 2004). Therefore, they are typically, only employed for cases involving critical/high value machine components/systems. For more comprehensive reviews of various concepts of automated/intelligent maintenance support techniques, refer to the following: (1) a review of various advanced digital vibration signal processing techniques given by Nandi (Nandi and Jack, 2004), (2) a comprehensive review of the applications of AI techniques for induction motor stator fault diagnostics provided by Siddique (Siddique, et al., 2003) and (3) a comprehensive review of various prognostic techniques/approaches provided by Carl (Carl, et al., 2004) such as experience-based prognostics, evolutionary prognostics, feature progression and AI-based prognostics, state estimator prognostics and physics-based prognostics (See also Barlas (Barlas, 2003) and Impact Technologies (Impact Technologies, 2005)).).

Examples of research work/implementation related to automated/intelligent maintenance support are: (1) Bo (Bo et al., 2000), investigated and demonstrated the use of neural networks for motor rolling bearing fault diagnosis, (2) Chen (Chen and Chris, 2002), investigated the use of transient vibration signal for machine fault diagnosis, (3) Déchamp (Déchamp et al., 2004), investigated and demonstrated the use of AI techniques for machine prognosis and diagnosis on an e-maintenance platform – PROTEUS (See also PROTEUS (2004)), (4) Devaney (Devaney and Eren, 2004), described the use of the FFT, wavelet-based techniques and neural networks for detecting motor bearing faults, (5) Goumas (Goumas, et al., 2002), investigated and demonstrated the use discrete wavelet analysis and statistical signal processing for the classification of washing machines vibration signals, (6) Hvass (Hvass and Tesar, 2004), proposed a new decision making method facilitating intelligent actuator condition based maintenance (DM/CBM), (7) Intelligent Maintenance Systems Center (2005, more details later), (8) Khanniche (Khanniche and Mamat, 2001), investigated and demonstrated the use of wavelet-based

techniques (Discrete Wavelet Transform (DWT)) for fault detection and diagnostics of 3-phase inverter systems etc.

One of the prominent examples of intelligent maintenance support tools is the Watchdog Agent, developed at the Intelligent Maintenance Systems Center (2005). The Watchdog Agent is a machine diagnostic and prognostic support tool, which is capable of detecting operation deviations and predicting the future trends of equipment (Yan and Lee, 2005; see also IMS, 2005). Once installed in an equipment system, it continuously evaluates and monitors equipment's *performance degradation* based on a set of selected parameter data, acquired from multiple sensors. Performance degradation assessments are performed using various signal processing, feature extraction, sensor fusion, performance evaluation and health diagnosis techniques (Djurdjanovic, et al., 2003; see also IMS, 2005). Figure 2.4 shows the integration of the Watchdog Agent with other components in an integrated intelligent maintenance system (IMS, 2005).

In cases involving service support for large-scale complex equipment systems/plants, the support process typically involves various parties present at different geographical locations, such as engineering firms, equipment vendors, maintenance firms etc. Several remote collaborative systems have been proposed. They are aimed at facilitating the participation and coordination of the various parties in a maintenance support process. Examples of such systems are the Problem-Oriented Multi-Agent-Based E-Service System (POMAESS) (Ren, et al., 2002) and the Service Virtual Enterprise (SVE) (Yoichi, et al. 2003).

In addition, in the efforts to facilitate maintenance data/information integration with other enterprise information systems (e.g. the Computerised Maintenance Management System (CMMS), Enterprise Asset Management System (EAMS), Enterprise Resource Planning (ERP), Supervisory Control and Data Acquisition System (SCADA) etc), various research efforts have been initiated. One of the most prominent examples of such efforts was initiated by the Machinery Information Management Open System Alliance (MIMOSA, 2004). MIMOSA is a non-profit-making organization

established to support the development and to promote the use of open information standards for facilitating data/information sharing between asset management/maintenance information systems and other information sectors (e.g. information available in control systems, operation management systems, material management systems, financial systems etc) in an organization (MIMOSA, 2004). The Open System Architecture for Enterprise Application Integration (OSA-EAI) is an XML-based specification, promoted by MIMOSA, for facilitating the implementation of an information infrastructure capable of efficient exchange of maintenance information. Figure 2.5 illustrated the roles of the OSA-EAI specifications and its relation to other relevant standards such as the ISA-95 (ISA, 2004) and OPC (OPC, 2003) (OpenO&M, 2004).

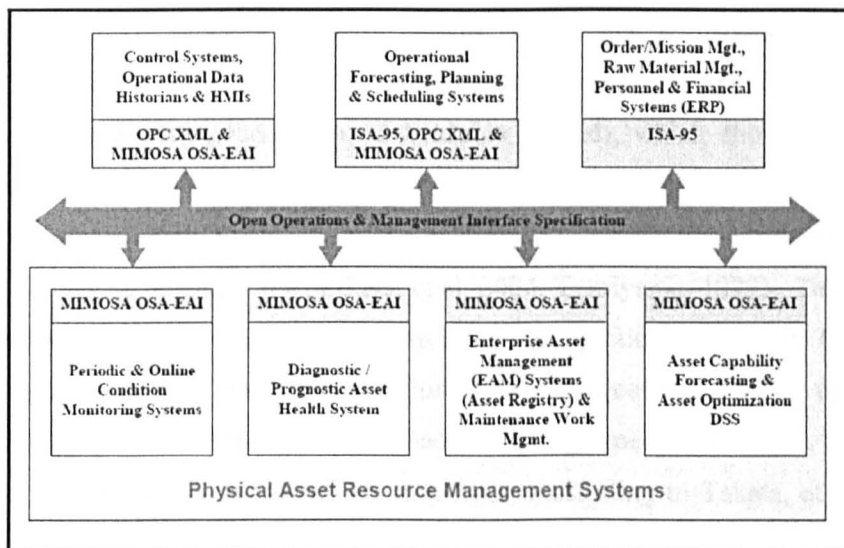


Fig. 2.7 MIMOSA's OSA-EAI for maintenance data/information integration with enterprise information systems (Courtesy of OpenO&M, 2004)

Besides, other similar initiatives (with different focuses), have also been initiated. Bangemann (Bangemann, et al., 2004) described a project aimed at creating an integration platform for distributed maintenance systems – PROTEUS. The main focus of the PROTEUS project was on creating an integration infrastructure (platform) for facilitating maintenance application integration. The project identified the following core

maintenance applications to be integrated via the platform (Bangemann, 2004; PROTEUS, 2004): (1) Web Portal, (2) Enterprise Resource Planning (ERP), (3) Computerised Maintenance Management System (CMMS), (4) Knowledge Management component, (5) e-Documentation Server, (6) Data Acquisition Server, (7) platform core component. Additionally, Déchamp (Déchamp, et al., 2004) described and demonstrated how Artificial Intelligence-based maintenance support tools (for diagnostics and prognostics) could be integrated with other information systems via the PROTEUS E-maintenance platform.

### 2.3.4 Life Cycle Support

With growing attention to the environment, it is recognized that there is a need to minimize environmental impacts caused by unsustainable manufacturing activities. It is proposed that to be **sustainable** there should be changes in current manufacturing practices, to have more focus on the **service-based business model** (in addition to the traditional focus on the **product-based business model**), which should advocate the minimization of material and energy consumption, maximization of resource re-use (e.g. via re-cycling) and at the same time, maintaining the ability to satisfy the needs of customers and to maintain profits (Takata, et al. 2004; Tomiyama, 1999). To achieve the goals, maintenance has been identified as an important function. However, Takata, et al. (2004) proposed that for achieving the aforementioned goals, there is a need for the conventional roles of maintenance to be broadened and perspective changed, i.e. it should be viewed as a **life cycle management function**. According to Takata, et al., it is no longer sufficient to just maintain the *physical life* of products, which is the traditional focus of maintenance activities. Takata proposed that the *functional life* of products also needs to be maintained (See Takata, et al. 2004, for further details about the concepts of *physical life* and *functional life*.). For this purpose, various concepts which could contribute to prolonging the *functional life* of products and minimizing the need for producing new products have been proposed such as self-maintenance, re-configure-ability, upgrade-ability, in-service product improvement, easily re-cycle-able products etc (Takata, et al. 2004; Tomiyama, 1999).

### 2.3.5 Discussion

Even though various commercial systems have been implemented successfully, further refinements are required for them to be used as service support tools for new generation manufacturing systems. It should be noted that the applications of most currently available commercial maintenance support solutions are generally limited to specific classes of constant speed rotary machinery, typically used in high-value plants such as motors (driving fans, pumps etc), turbines, compressors etc. Machine builders/suppliers for manufacturing equipment such as CNC machines, textile machines etc, have also started to provide some level of remote service support for their global customers. In most cases, the service support process may still be considered as rudimentary and generally still requires the active involvement of remote experts. Most commercial solutions, in general, have not taken advantage of currently available intelligent/automated maintenance-support-tools/strategies and other potentially useful technologies such as 3D virtual technology etc.

Despite various recent research efforts, which have successfully demonstrated the feasibility and benefits of automated/intelligent maintenance support tools, the implementation of such tools for new generation manufacturing systems remains challenging as a result of their (new generation manufacturing systems' and support tools') intricacy and the need to cater for a greater degree of uncertainty (Phillip, 2004). It should also be noted that most existing commercial tools are designed for only certain classes of machinery, which typically having a single point of operation (i.e. they have a narrow operating range). The implementation of automated maintenance support tools for devices having a wide operating range such as high-performance servo-controlled actuators used in special-purpose mechanisms is generally, more challenging and resource-consuming (Hvass and Tesar, 2004). In most cases, successful implementation of automated support systems/tools often requires experts (humans) to work closely with equipment (in particular, in the initial operation phase, which may prolong the period of time, support personnel need to stay onsite). This often implies the need for frequent site visits and access to a comprehensive set of equipment current (which need to be collected onsite) and historical operational data/information (Carl, et al., 2004; Sutherland, et al.,



2003). In some cases (e.g. involving critical equipment), laboratory tests may need to be carried out, which may involve destructive tests. Such approaches are generally resource consuming and inefficient. As a result, it may not always be feasible, particularly for cases involving new generation manufacturing systems, where a large quantity of data/information needs to be dealt with and where historical reference is limited. Generally, in most existing remote service support strategies, there is a lack of an efficient and cost effective mechanism for the remote implementation, assessment, improvement and re-configuration/upgrade support for intelligent/automated maintenance-support-tools. Accordingly, further research into a more efficient deployment/implementation and in-service support strategy is required to allow intelligent/automated maintenance support tools to be leveraged more cost-effectively and to cater for uncertainties during the in-service life of equipment.

Due to the complexity of new generation manufacturing systems, it is necessary to continuously improve and optimise equipment performance, and to minimise their maintenance requirements/to improve service-ability, during the equipment's service lifecycle (Takata, et al., 2004). However, most existing remote support systems are limited in terms of capability as tools for supporting re-configuration/optimisation support for only small-scale systems such as CNC machines and for limited aspects of equipment systems such as control parameter re-configuration, control system software component upgrade etc. In general, there is a lack of the integration of a systematic long-term strategy for supporting equipment design out maintenance such as for minimising its maintenance requirements, improvement of service-ability etc, especially for complex manufacturing systems. Furthermore, there is also a lack of an efficient strategy for supporting equipment improvement in terms of functionality and performance. For supporting cost-effective in-service improvement and optimisation of complex new generation manufacturing systems, current remote support systems/strategies need to be further improved. Additionally, an effective remote data management and visualisation tool is also required to facilitate the remote access, visualisation and re-use of complex sets of equipment operational data/information. However, as the visualisation techniques used in most current web-based/remote maintenance support systems are 2D-based

(including picture/video-based) (Such as those shown in figure 2.1 and 2.2.), they are insufficient/inefficient as remote visualisation tools for complex new generation manufacturing systems (which are typically mechatronic in nature). Further research is necessary into how to improve the visualisation capability of existing remote visualisation tools. One particular area, which has not been sufficiently explored (and exploited), is the use of 3D-based visualisation tools, especially on how it can be integrated with various 2D-based/video-based visualisation tools and maintenance-support-tools, in a network/Internet framework (See chapter 3 for a review of the applications of 3D virtual technology in machine service support.).

The concept of lifecycle support, which advocates more focus on the service-based business model, as proposed by Takata (Takata, et al., 2004) and Tomiyama (Tomiyama, 1999) also served as a motivation for exploring the potential and feasibility of extending the range of support services for new generation manufacturing systems and to explore how extended support functions can be integrated with conventional maintenance support functions. It is expected that such extended services could benefit both the machine builder/supplier and the machine user. From the perspective of the machine builder, the expected benefits are: (1) new business opportunities, e.g. when there are changes in the customer requirements for an existing installation, the machine builder/supplier could fulfil such needs at a relatively low cost via optimized re-use of existing equipment instead of the more costly option of constructing a complete new installation etc, and (2) reduce environmental impacts, i.e. able to fulfil the requirements of new legislation related to the environment (of course, without compromising customers' satisfaction and to maintain profits). To the machine user, the potential benefits are: (1) more comprehensive support from the machine builder/supplier at lower costs and (2) allowing the machine user to respond to market changes more rapidly and cost-effectively. However, most current machine service support strategies have, generally, not integrated this aspect of service support functions into their service support strategies/systems. In order to reap the potential benefits of the service-based business model, further research into more advanced service support strategies capable of

seamlessly integrating conventional maintenance support functions and extended service support functions is essential.

## **2.4 Emerging Standards for Maintenance Support Systems**

### **2.4.1 Introduction**

This section (2.4) presents an overview of some of the emerging open standards/architectures/specifications in the area of machine service support, in particular, those related to Condition-based Maintenance (CBM). The focus of this review is the Open System Architecture for Condition-based Maintenance (OSA-CBM, 2003). A more comprehensive review of various open standards/architectures/specifications related to CBM was given by Bengtsson (Bengtsson, 2004).

### **2.4.2 Emerging Standards/Architectures/Specifications Related to Machine Maintenance**

One of the prominent standards related to CBM is the Open System Architecture for Condition-based Maintenance (OSA-CBM, 2003). The OSA-CBM initiative was initiated to answer the need in industrial, commercial and military applications for an open communication interface standard for distributed automated/intelligent CBM software components/modules (Lebold, et al., 2003a; OSA-CBM, 2003). The OSA-CBM framework was developed based on various existing/emerging standards such as the MIMOSA CRIS (MIMOSA, 2004, note that MIMOSA has been mentioned in sub-section 2.2.3) and IEEE 1451.2 (IEEE Std 1451.2-1997, 1998). The OSA-CBM architecture provides a framework for a CBM system and specifies the communication interfaces between the various classes of components/modules defined within the framework. It does not, however, dictate the design of the internal structure of each individual component/module.

The OSA-CBM architecture consists of seven classes of generalized components/modules or layers (Lebold, et al., 2003b; OSA-CBM, 2003), as depicted in figure 2.5: (1) Sensor Module, (2) Signal Processing Module, (3) Condition Monitor Module, (4) Health Assessment Module, (5) Prognostic Module, (6) Decision Support Module and (7)

Presentation Module. The implementation of the OSA-CBM schema was demonstrated using several middleware technologies, such as: (1) the Common Object Request Broker Architecture (CORBA, 2005), (2) Distributed Component Object Model (DCOM, 2005) and XML over HTTP (SOAP, 2005). Details of implementation was reported by Lebold (Lebold, et al., 2003a), Gilbertson (Gilbertson and Chidambaram, 2002) – CORBA/XML-based implementation, Lebold (Lebold, et al., 2003c) – DCOM-based implementation and Lebold (Lebold, et al., 2003b) – XML over HTTP-based implementation.

Besides, there were also a number of relevant standards/specifications/guidelines developed. Some of the standards are: (1) IEEE 1451 (IEEE Std 1451.1-1999, 2000; IEEE Std 1451.2-1997, 1998; IEEE Std 1451.3-2003; IEEE Std 1451.4-2004) – a family of smart transducer interface standards, developed to facilitate the integration and interoperability of smart devices (sensors and actuators) from different vendors, in a network environment (See sub-section 2.5.2 for a more detailed discussion about the IEEE 1451.) and (2) ISO 13373-1 - Condition Monitoring and Diagnostics of Machines, a set of general guidelines for measurement and data collection procedures (ISO 13373-1, 2002).

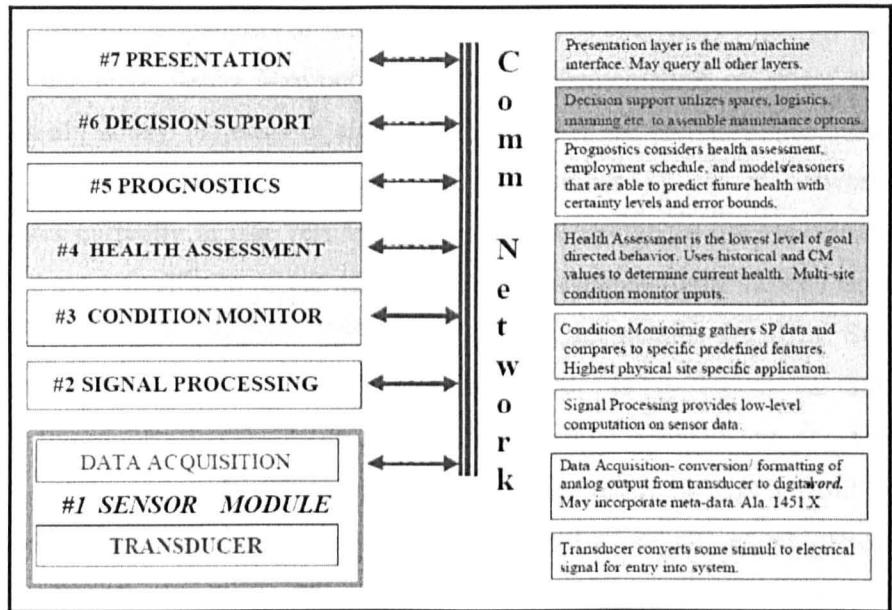


Fig. 2.8 Classes of OSA-CBM components/modules (Courtesy of OSA-CBM, 2003)

### 2.4.3 Discussion

The emergence of open standards/specifications have presented new opportunities that if gaining sufficient industrial acceptance would facilitate the integration, reduce the implementation and maintenance costs of commercial off-the-shelf (COTS) maintenance support solutions. The OSA-CBM is particularly relevant to this research study. By incorporating such (or similar) architecture, it is expected to improve the scalability and flexibility of a machine service support system for complex/large-scale machine systems.

## 2.5 Sensors and Integrated Data Acquisition

### 2.5.1 Introduction

This section (2.5) is intended to provide the reader with some background information about various current advances in sensor technologies, presented in sub-section 2.5.2 and data acquisition technologies, presented in sub-section 2.5.3.

### **2.5.2 Current Developments in Sensor Technologies**

In general, the benefits of smart sensors have not been fully exploited in industry. Some of the main issues surrounding current implementation of smart sensors are (Zhang, et al., 2004): (1) costs of smart sensors, which are currently, much higher than those of traditional sensors and (2) a large number of sensor network/fieldbus technologies currently in use, resulting in high implementation and maintenance costs. One of the most significant recent developments, in response to the various issues, is the emergence of various standards (IEEE 1451 family, for details, see IEEE Std 1451.1-1999, 2000; IEEE Std 1451.2-1997, 1998; IEEE Std 1451.3-2003; IEEE Std 1451.4-2004) for transducers and the introduction of commercial products compliant with such standards. As mentioned in the previous section, the IEEE 1451 is a family of smart transducer interface standards, developed to facilitate the integration and interoperability of smart devices (sensors and actuators) from different vendors, in a network environment. The emergence of the IEEE 1451 is driven mainly by the need to reduce the implementation costs for network smart transducers (Note that this review focuses on smart sensors rather than smart actuators.).

There have been extensive research and development efforts focusing on the implementation based on the IEEE 1451. Among others, Lee (Lee, et al., 2002) proposed a framework for the integration of the IEEE 1451 with the MIMOSA/OSA-CBM architecture. The work focused on identifying links between the IEEE 1451 family of standards and the MIMOSA/OSA-CBM architecture. The study indicated the feasibility of linking the various standards. In addition, there have been a number of other research work/case studies focusing on different aspects of implementation related to the IEEE 1451, among others: (1) wireless interfaces for the IEEE 1451 (Baer and Lally, 2000; Gilsinn and Lee, 2001), (2) software platforms for smart sensors (Lei and Wu, 2003) and (3) case studies of applications of the IEEE P1451.4 (Potter, 2002).

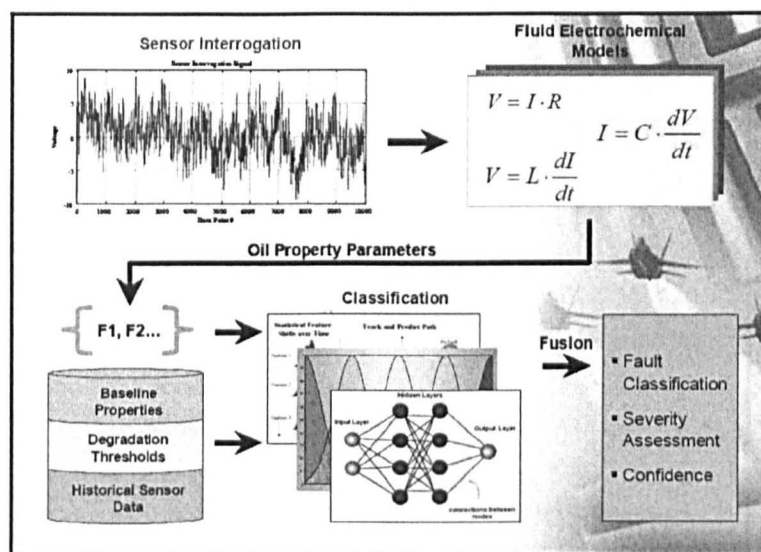


Fig. 2.9 The Smart Oil Sensor (Courtesy of Impact Technologies, 2005)

A survey of sensor manufacturers/suppliers indicated that there were a number of manufacturers producing IEEE 1451-compliant products. Examples of manufacturers supplying IEEE 1451-compliant products are: (1) The Modal Shop (The Modal Shop, 2004), supplying various IEEE 1451-compliant sensors and interface kits, (2) Analogue Devices (Analog Devices, 2004), supplying various IEEE 1451-compliant sensors and analogue-to-digital converters (ADCs), (3) PCB Piezotronics (PCB Piezotronics, 2004), supplying various IEEE 1451-compliant sensors and instrumentation products and (4) TMI – Telemonitor Inc. (TMI, 2004), supplying a number of the IEEE 1451-compliant Smart Transducer Interface Modules (STIMs). Besides, there are a number of commercial smart sensor products (which may not comply with the IEEE 1451) for applications in machine maintenance support. Some examples of such products are: (1) the Smart Oil Sensor and Hydraulic Pump Life Monitor from Impact Technologies (2005) and the Octavis vibration sensor from Ifm Efector (2005). Figure 2.8 shows the embedded processing functions of the Smart Oil Sensor (Impact Technologies, 2005), consisting of components for various purposes such as: classification, fusion and assessment.

### 2.5.3 Current Developments in Data Acquisition Technologies

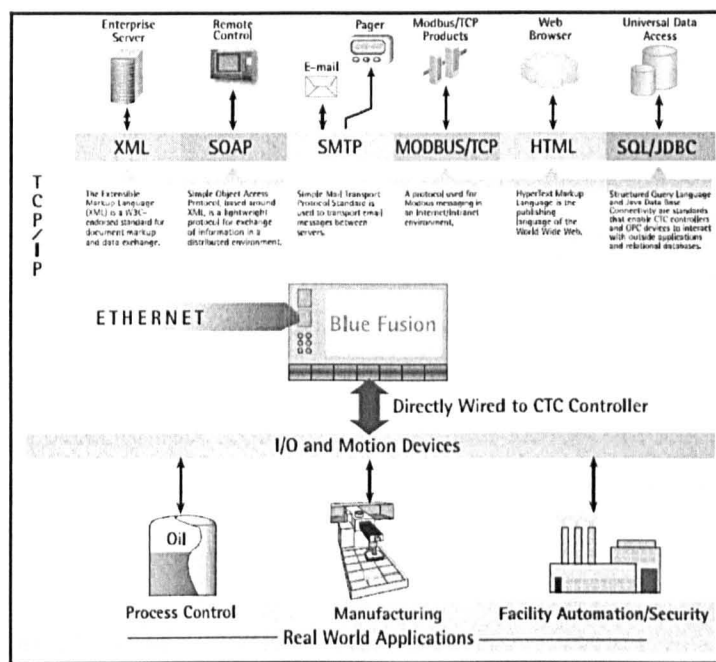


Fig. 2.10 Network communication capabilities of an integrated machine controller (the Blue Fusion controller, courtesy of Control Technology Corporation (Control Technology, 2005))

A survey of commercial machine control products indicated that there were trends towards tighter integration between the control system and the data acquisition system. The survey found a number of products with built-in maintenance support capabilities. Typically, these integrated control solutions combine the functions of a typical control system (both the logic and motion control) with additional features for data acquisition and monitoring such as extra input/output (both digital and analogue, for connection with external sensors), built-in data logger (with/without built-in data buffers), application programming interface (API) and network communication capabilities (e.g. serial (RS232, RS485 etc), TCP/IP Ethernet etc), into a single highly integrated compact solution. They allow additional external sensors to be connected to the control system for data acquisition purposes. The integration also facilitates the acquisition of equipment control data/information used internally by the control system. Examples of such control



solutions are: (1) the Blue Fusion controller from Control Technology Corporation (Control Technology, 2005) (See figure 2.9 for an example.), the BX2 motion and machine control from Berkeley Process Control Inc (Berkeley Process Control, 2005), the MAX 2030 digitalPOWER Distributed Servo Controls from Agile Systems Inc. (Agile Systems, 2005) and SM800 PLC (with built-in data logger and communication controller) from Nota Bene Technology (Nota Bene Technology, 2005). It should be noted that, however, typically, the logging capabilities of such control systems are relatively limited, e.g. lower sampling rate, smaller data buffer etc, when compared with dedicated data acquisition systems. In general, they are suitable for most applications where low sampling rates (e.g. within the range of 1 kHz) are acceptable. Dedicated high-speed large capacity data acquisition system and sensors are still required for the acquisition of data associated with physical parameters having high change rate such as vibration, electric current etc.

#### **2.5.4 Discussion**

In general, various advances in sensor and data acquisition technologies, have presented new opportunities for the implementation of a more cost-effective, flexible and scalable remote machine monitoring system (by reducing the implementation and maintenance costs for the data acquisition system), in particular, for complex new generation manufacturing systems. Some of the potential benefits of such technologies are (from the perspective of machine builders/suppliers): simplified data acquisition system design, implementation (such as by reducing the number of external sensors and signal-conditioning components), maintenance and upgrade/re-configuration process.

#### **2.6 Chapter Summary**

This chapter has presented an overview of current developments in the area of machine service support. It has identified various issues and opportunities with regard to the implementation of a more cost-effective and comprehensive service support strategy/system for new generation manufacturing systems. The identified issues can be summarized into the following:

- (1) The lack of a cost effective and efficient mechanism for the remote implementation, assessment, improvement and re-configuration/upgrade support for intelligent/automated maintenance-support-tools.
- (2) The lack of a comprehensive and efficient mechanism for the continuous in-service improvement and optimisation support (both short and long term) for complex new generation manufacturing systems.
- (3) Limitations of existing approaches to the remote management and visualisation of a large quantity of multivariate and multi-level equipment data/information.
- (4) The lack of an efficient strategy for the implementation of extended service support functions such as equipment re-configuration, upgrade and expansion support for complex new generation manufacturing systems.
- (5) The lack of a strategy to seamlessly integrate extended service support functions and remote maintenance support functions into a more integrated machine service support strategy/system.

Additionally, various developments, which have the potential for facilitating the realisation of a more advanced machine service support strategy/system for new generation manufacturing systems, can be summarized into the following:

- (1) Advances in the area of intelligent/automated Condition-based Maintenance (CBM) techniques.
- (2) Advances in communication and information technologies.
- (3) Emergence of various open architectures/standards related to the area of machine maintenance support.
- (4) Advances in sensor and data acquisition technologies.

The next chapter (chapter 3) presents a review of the developments and applications of 3D virtual technology in the area of machine service support.

## **Chapter 3**

# **Review of the Developments and Applications of 3D Virtual Technology in Machine Service Support**

### **3.1 Introduction**

This chapter presents a review of current developments and applications of 3D virtual technology in the area of machine service support. It focuses on applications in the following four main areas: (1) maintenance operation design and planning, presented in section 3.2, (2) maintenance operation training, presented in section 3.3, (3) onsite maintenance support, presented in section 3.4 and (4) remote monitoring and collaborative maintenance support, presented in section 3.5. Section 3.6 presents an overview of an industry-based Swedish project (and its link with this research study) of which the author is involved in, where 3D virtual engineering tools have been integrated with the machine maintenance support and machine control system. The last section (3.7) summarises the findings of the literature survey and concludes the motivations for undertaking this research study.

### **3.2 Maintenance Operation Design and Planning**

#### **3.2.1 Introduction**

The review in this area has been delimited to the applications of 3D virtual engineering tools for supporting the design and planning of the **technical** aspects (e.g. for the design and planning of procedures required for complex maintenance work) of maintenance operations rather than the strategic/managerial aspects.

#### **3.2.2 Commercial Solutions and Related Research Work**

The survey has indicated that 3D-based virtual engineering tools have been used successfully for supporting machine maintenance operation design and planning (even though its applications are, currently, still limited to certain high-value industries). There are various commercial 3D simulation tools, which provide capabilities for supporting maintenance operation design and/or planning. Examples of such commercial simulation

tools are: Envision Ergo (Delmia, 2005c), DMU Fitting Simulator 2 (FIT, 2005), Virtools software suites (Virtools, 2005), Walkinside (Walkinside, 2005) etc. The applications of such support tools are generally more prominent in maintenance support for high value plants/equipment such as chemical plants, power plants, large ships, aircrafts etc.

In the plant/equipment design phase, the simulation tools are typically used for designing strategies/procedures for maintenance tasks/operations and to validate (using 3D-based simulation) the maintainability and serviceability of plants/equipment (i.e. to support design for maintainability/serviceability). This allows the design for all support tools/procedures (e.g. maintenance procedures, personnel training tools, special maintenance support tools etc) required for plant/equipment maintenance to be carried out (more effectively) in parallel with the plant/equipment design process. In the operational phase, the simulation tools are used as planning tools for complex maintenance operations. Typically, such planning would involve the feasibility study of a maintenance operation (under a set of constraints such as allocated budgets, time constraints, spatial constraints, health and safety risks etc) and its relation to other operations (in order to avoid operation conflicts). It is then used for planning how specific sets of maintenance procedures should be carried out such as how a disassembly/re-assembly process should be performed, what specific tools to use etc. Such planning is particularly important if it involves large/heavy components/equipment.

Additionally, there have also been several (and ongoing) research/development efforts aimed at improving the various aspects of existing 3D-based maintenance operation planning tools/techniques. In an effort to reduce human workloads in planning complex maintenance procedures (e.g. those which need to deal with large numbers of spatial constraints), an Esprit LTR project called MOLOG (MOLOG, 1999; Schmidzberger and Bouchet, 2001) was initiated, aimed at integrating automated motion planning tools into a 3D virtual environment for assisting humans in the maintenance work planning process. As equipment maintenance work often requires the disassembly and assembly of components, various research and development efforts (Jian, et al., 2002; Marcelino, et al., 2003 etc) were also conducted for improving existing techniques/tools

for supporting design for assembly/disassembly. Latterly, a 3D-maintenance project (Laureillard and Nouailhas, 2005) has been initiated and is currently underway at Electricité de France (EDF), France. It is aimed at optimizing maintenance work for a nuclear power plant. An initial prototype has demonstrated how 3D-based simulation tools can be used to support maintenance planning/preparation for a plant outage. The developed toolsets have also demonstrated how a 3D-based visualization tool can be used to support the execution of maintenance work and to capture experience/knowledge relevant to a maintenance operation. The research into the applications of 3D-based simulation techniques for equipment fault behaviors simulation and prediction has also reported (Baydar and Saitou, 2004; Walker and Shirkhodaie, 2001). Baydar (Baydar and Saitou, 2004) described the use of Monte Carlo simulation with 3D-based visualization for the prediction of potential equipment errors and their probability of occurrence. The outputs of the simulation could then be used for supporting equipment design, maintenance planning, diagnostics and recovery.

### **3.2.3 Discussion**

In general, various commercial products and research efforts have demonstrated how 3D-based virtual engineering tools can be used for supporting maintenance operation design and planning. By incorporating such tools into a remote machine service support system, it has the potential for providing the following benefits (mainly from the perspective of machine builders/suppliers, in relation to providing service support for new generation manufacturing systems):

- (1) Allowing machine experts/engineers to plan (remotely) in advance an optimized maintenance work sequence and to generate clear and concise 3D-based animated maintenance instructions.
- (2) The generated 3D-based animated/simulated maintenance work instructions could then be used in one of the following ways:
  - (a) Used by machine builders/suppliers' experts/engineers as a reference guide to perform a maintenance service onsite/offsite.
  - (b) Used by machine builders/suppliers' junior service engineers/technicians as a reference guide to perform a maintenance service onsite/offsite. This

has the advantage of relieving machine experts/engineers of routine maintenance work that could be performed by junior engineers/technicians as long as clear instructions are provided (which in this case using a 3D-based animated instructions).

(c) Used by machine users' engineers/technicians as a reference guide to perform a maintenance service onsite (with or without support from remote machine experts/engineers).

(3) A validated (both virtually and practically) maintenance work instruction set could then be re-used for future training of equipment operators, technicians, engineers of both the machine user and machine builder/supplier.

### **3.3 Maintenance Operation Training**

#### **3.3.1 Introduction**

Maintenance operation training is one of the main areas where 3D-based simulation tools have been used extensively and successfully. This section (3.3) presents a review of various 3D-based commercial products for maintenance operation training. In addition, a review of current/recent research efforts in various related areas is also provided.

#### **3.3.2 Commercial Solutions**

A wide range of 3D-based commercial products for maintenance training is currently available on the market. Examples of such training tools are: CAE Simfinity Virtual Maintenance Trainer (CAE, 2005), NGRain software suites (NGRAIN, 2005), Right Hemisphere software suites (Right Hemisphere, 2004) Virtual Manuals Enterprise Platform (ParallelGraphics, 2005a; ParallelGraphics, 2005b) etc. There are, generally, two typical categories of functionality provided by these tools: (1) 3D-based documentation ('virtual manual') and (2) interactive 3D-based virtual training environment. In the first category, the 3D CAD data of equipment is re-used in such a way that links are set up between the 3D CAD data and all available equipment technical data/information (including design, operational and maintenance-related data) in a 3D virtual environment. This provides equipment maintenance personnel with an intuitive

3D-based technical training manual (which could of course be used as technical reference for supporting the execution of maintenance work, see section 3.4 for details). Typically, web-based visualization tools are also provided to facilitate users in accessing data/information of the 3D-based documentation. In the second category, a 3D-based virtual environment is used to present known machine failures/faults scenarios and corresponding maintenance actions/procedures using 3D-based animation. It effectively acts as a virtual training instructor relieving a human instructor of some of routine training tasks. The maintenance scenarios are typically presented in the form of either pre-defined interactive 3D animation sequences or dynamic 3D simulation sequences (i.e. without any predefined sequences).

### **3.3.3 Related Research Work**

Even though 3D-based training tools have been used successfully, there are several aspects of existing tools, which require further refinement. From the trainer's perspective, considerable programming effort is typically required to create complex training scenarios, which makes the tools less user-friendly (Bluemel, et al., 2003; Ishii, et al., 1998). In such cases, experts in both maintenance training and computer programming are required in order to take full advantage of the capabilities of the simulation tools. There have been several research and development efforts attempting to address some of the key issues: (1) limitations in terms of the realism of a virtual training environment and (2) complexity associated with constructing complex maintenance scenarios (from the perspective of the trainer). Among others, Ishii (Ishii, et al., 1998) described a design environment for supporting the construction of maintenance training scenarios in a 3D-based virtual environment (for training personnel of a nuclear power plant). It provides the maintenance trainer with visual construction tools for creating maintenance training scenarios, instead of text-based programming environments. The basic idea is to reduce the workloads of trainers by minimizing the need for using text-based programming languages in creating complex maintenance training scenarios. Subsequently, Bluemel (Bluemel, et al., 2003) proposed a further improved architecture for such a tool. In general, Bluemel's work focused on improving the following aspects (Bluemel, et al., 2003): (1) interactivity – for improving the realism of training by

allowing trainees to more actively involve in a training session, (2) flexibility – allowing a training environment to be used (via rapid re-configuration) for different training scenarios and (3) user-friendly authoring – allowing efficient construction of complex maintenance scenarios. Besides, most current commercial solutions provide only limited interaction realism during training sessions (limited to typical PC input devices such as a mouse, keyboard and joystick). There have been (and ongoing) research and development efforts aimed at improving the degree of realism of interaction in a virtual training environment via the use of immersive 3D visualization tools (Corvaglia, 2004; Murray and Fernando, 2003 etc). Among others, Corvaglia (Corvaglia, 2004) described an immersive 3D virtual training environment called ‘immersive VIRTUAL TRAINING’ (iVT) application. For improving the training realism, the iVT makes use of devices such as 3DOF sensors, data-glove and head mounted display (HMD). The use of data-glove allows trainees to interact more naturally through hand/finger movements instead of the less natural interaction methods used in conventional tools. In addition, successful use of augmented reality-based visualisation techniques for improving training (instead of pure virtual reality-based visualisation) realism has also been reported (Francisco, 2002).

### **3.3.4 Discussion**

In general, there are two main limitations associated with most current 3D virtual training tools: (1) limitations in terms of the realism of a virtual training environment and (2) complexity associated with constructing complex maintenance scenarios (from the perspective of the trainer). Despite various limitations of existing 3D-based training tools, they have been used successfully. They have provided a significant improvement over traditional 2D-based/paper-based training tools. One particular aspect crucial to the effectiveness of such a tool (in particular, in relation to using it for new generation manufacturing systems) is the need for the tool to be updated/reviewed regularly, as necessary (e.g. when there is a change in equipment, which affects the accuracy of parts of the training tool). This could be achieved by integrating the training tool into a machine service support system in such a way that it could be reviewed and updated efficiently (whenever necessary) by both the machine user and machine builder. In the long term, such integration is expected to further streamline the maintenance process, in



particular in terms of allowing less experienced personnel to perform most maintenance work, relieving the expert of some/most of routine maintenance support tasks.

### **3.4 Onsite Maintenance Support**

#### **3.4.1 Introduction**

This is another area where 3D virtual technology has been used extensively. For ease of discussion, it has been further categorised into the following: (1) 3D-based maintenance management, (2) onsite maintenance assistance.

#### **3.4.2 Commercial Solutions and Related Research Work**

In the first category (1) of applications, a 3D visualization tool is typically integrated with various data/information sources (databases) and asset/maintenance management application modules (such as the Computerised Maintenance Management System (CMMS), Enterprise Asset Management System (EAMS), Enterprise Resource Planning (ERP) etc). They are typically designed as plant/equipment maintenance management tool for the machine user, used for supporting maintenance of complex/large-scale plants such as chemical plants, power plants, large ships etc. Examples of such commercial solutions are: Cadmatic Maintenance software (Cadmatic, 2005), myShipVi (Intergraph, 2005), Virtual Mill (Jaakko, 2005), Walkinside (Walkinside, 2005), ProcessLife (ProcessLife, 2005) etc. The integration allows users to access equipment data/ information and maintenance management tools via an interactive 3D-based user interface (instead of the traditional 2D-based user interface). This allows maintenance personnel to retrieve and correlate equipment operational and maintenance data/ information, identify/locate specific components and to manage maintenance operations (such as work schedules, work orders, maintenance reviews, downtime records, service records etc), efficiently. Typical features of such tools are: users can navigate through the 3D virtual space intuitively ('walkthrough'), web-based visualization components (typically in the form of a plug-in for an Internet browser), interactive 3D virtual components with links to equipment data/information (such as equipment datasheets/ specifications, manufacturers' information, service history etc), automatic reporting/alert/ reminder tools and additional access links to external data

sources/systems. In addition, some commercial products also provide tools for facilitating integration with equipment data acquisition systems, allowing access to low level equipment operational/parameter data/information such as that associated with energy consumption, volume, temperature, pressure etc.

An example of such systems is the Visualisation Decision Support System (VDSS) (Jiang, et al., 2003). The VDSS was developed for the condition monitoring of Hydro-electric Generation Units (HGU's). It consists of a 3D-based visualisation system integrated with the equipment control system and maintenance support systems (e.g. SCADA systems and machine expert systems), in a network environment (note that the Visualisation Decision Support System (VDSS) was designed for use on a local area network (LAN)). The developed 3D-based visualisation environment showed how the complex structures of HGU's could be visualized effectively. It also showed how a 3D virtual environment could be used to efficiently locate sources of equipment faults/failures. The field evaluation of a prototype of the support system has demonstrated the benefits and feasibility of integrating 3D virtual technology with machine control and maintenance support systems for improving condition monitoring for complex equipment systems.

In the second category (2) of applications (i.e. for providing onsite maintenance assistance), a 3D-based visualization tool is typically used in a form called augmented reality. A typical augmented reality system is created by overlaying a 3D virtual view (in conjunction with 2D graphics/text and additional 3D views) onto a human real world view either through a transparent screen or displayed on a computer monitor screen. In these applications, an augmented reality-based maintenance assistance tool is designed to be portable in such a way that it could be used for providing additional data/information in real-time without distracting the maintenance personnel (e.g. allowing the maintenance personnel to maintain view on the subject, does not require the maintenance personnel to move his/her hands away from the subject just to operate the maintenance assistance tool or any additional manuals etc). Such a tool allows the maintenance personnel to focus on his/her work with assistance provided, as appropriate, by the tool. Data/information

provided by the tool may consist of one or more of the following: camera views, 2D/3D virtual models, maps, component details (such as identification details, specifications, manufacturer details etc) and maintenance instructions/recommendations. One of the main limitations of the earlier versions of prototypes was that they were typically bulky, making them unsuitable for real life applications. Latterly, several research efforts have been made (and some ongoing) towards minimizing the physical size and to improve the capabilities of such tools. Some prominent examples of such research efforts have been reported by Schwald (Schwald and Laval, 2003), Laval (Laval, et al., 2002 – Project STARMATE) and Makri (Makri, et al., 2005 – Project ULTRA, ongoing).

### **3.4.3 Discussion**

In relation to the first category (1) of applications, most tools have been designed specifically for the machine user (i.e. the plant/equipment owner), as a plant operation and maintenance management tool, in particular, for large plants/equipment. In general, the potential of extending the functionality of such 3D-based visualization tools for the machine builder/supplier, for supporting remote machine service support activities, has not been sufficiently explored. Even though some of the tools allow the machine user to access low level plant/equipment operational data, they are generally insufficient, for them to be used by the machine builder, for providing service support for complex manufacturing systems. There is also a lack of integration of the visualization tools with automated/intelligent maintenance-support-tools, in particular, there is no efficient and systematic support strategy for the implementation of the maintenance-support-tools. In addition, the visualization aspect of the tools needs to be improved for more efficient visualization of complex mechatronics systems (typical new generation manufacturing systems). See section 3.5 for more detailed review of the applications of 3D virtual technology for remote machine monitoring and collaborative maintenance.

With regard to the applications in the second category (2), the tools are generally based on pre-generated data/information stored in a database. In certain cases, such as when pre-generated maintenance instructions are insufficient/inaccurate, support from remote experts/engineers would be required. In such cases, it may be beneficial to

integrate the portable maintenance assistance tool with a remote maintenance support system in such a way that it allows real-time bi-directional communication and data/information sharing between the maintenance personnel and the remote expert. This has the potential for improving the cost-effectiveness and efficiency of a remote machine service support strategy.

### **3.5 Remote Monitoring and Collaborative Maintenance**

#### **3.5.1 Introduction**

In general, this is an application area where the potential of 3D virtual technology has not been extensively exploited, in particular in relation to their applications for supporting new generation manufacturing systems. It has been found that most existing remote monitoring and collaborative maintenance support systems (details of review outcomes have been presented in chapter two) are still based mainly on 2D-based visualization tools. Even though there have been several research efforts (which have successfully demonstrated certain aspects of the potential) attempting to promote the use of 3D-based visualization tools for applications in remote machine maintenance support, it has been found that the potential of such tools have not been sufficiently explored. One potential application area for 3D virtual technology is their use for creating a platform for integrating various existing maintenance support strategies/tools/techniques (various strategies/tools/techniques have been presented in the previous sections of this chapter and chapter 2). Such integration has the potential for improving the effectiveness of existing remote machine service support systems, particularly, for complex new generation manufacturing systems. The following sub-section presents reviews of some of the pertinent work in this area.

#### **3.5.2 Related Research Work (Including Discussion)**

In general, most proposed solutions were based on the integration of 3D-based visualisation technology with remote video technologies and network/Internet technologies. There have been various 3D-based remote/web-based monitoring and control strategies/systems proposed and demonstrated by a number of researchers (Marco, et al., 1999; Pasek, et al., 2001; Wang, et al., 2002). Most research was focused

on optimizing the real-time performance of the remote control and monitoring system. Machine feedback data (such as axis position, speed etc) was typically acquired via remote sensors, which was used to update, in real-time (or near real-time), an animated 3D virtual model (viewed via a web browser) representing a real machine system. Generally, such systems did not consider the various aspects essential to machine service support.

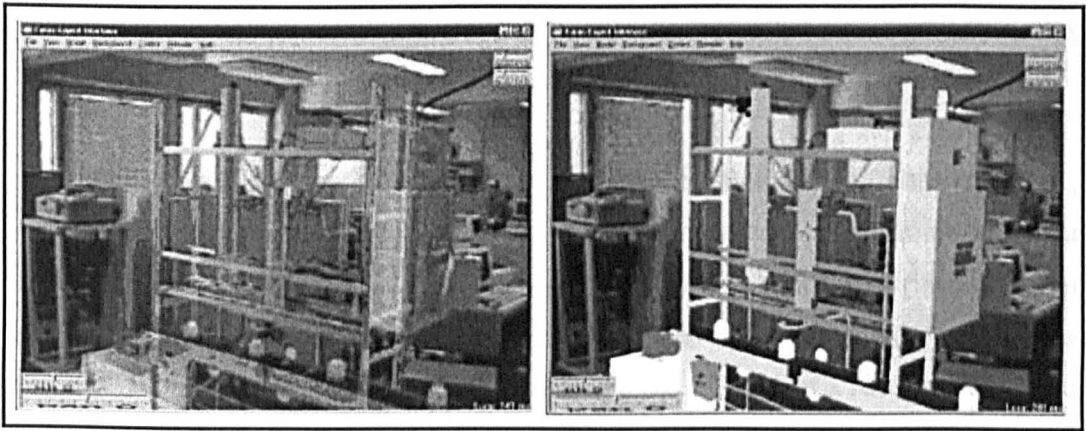


Fig. 3.1 Augmented reality-based remote visualisation (Courtesy of Panu, et al., 1999)

Meanwhile, several researchers have attempted to explore how web-based 3D visualisation technologies could be used for improving remote machine maintenance support strategies/tools. Among others, an augmented reality-based remote maintenance support system was first proposed by Panu (Panu, et al., 1999). The proposed system was designed as a remote collaborative maintenance support tool for facilitating communication between remote experts and onsite maintenance personnel during a collaborative maintenance service session. For remote visualisation purposes, the system consisted of cameras located at the machine site coupled with a PC-based remote visualisation tool located at the machine expert's site. The remote visualisation tool was based on an augmented reality system where a 3D-based model (and other 2D graphics and additional 3D-models) is overlaid onto the video view on a PC monitor. Figure 3.1 shows a view of the main user interface of the augmented reality-based visualisation system. In general, the system allowed maintenance work to be performed without

requiring a remote expert to be present at the machine site. It also provides tools to allow remote experts to acquire and visualize selected equipment process data, which was transferred in real-time. It should however be noted that the proposed strategy did not take full advantage of intelligent/automated maintenance-support-tools for supporting various maintenance support functions. It served mainly as a communication tool to allow remote experts to communicate instructions to and obtain feedback from onsite maintenance personnel. In other words, remote experts had to rely on the assistance provided by onsite maintenance personnel for most support activities including troubleshooting/diagnostics.

Subsequently, a similar strategy was proposed by Bellamine (Bellamine, et al., 2002). The main difference between the strategy proposed by Bellamine and that proposed by Panu was the use of a remotely controlled robotics arm (instead of an operator (a human)) for the acquisition of equipment operational data. Bellamine demonstrated how a vibration sensor attached to the end effector of a robotics arm could be used to collect vibration data from equipment at multiple points. It adopted augmented-reality based techniques similar to that described by Panu (Panu, et al., 1999). While the strategy may minimize the need for maintenance personnel to be present at the machine site and reduce the number of permanently installed sensors, it may not be practical/sufficient for cases involving complex/compact new generation manufacturing systems. In such cases, due to various spatial constraints, most internal components/parts /points of a complex machine system may not be accessible to a robotic arm, where strategies using permanently installed sensors may be more appropriate. It may also be observed that the strategy is suitable only for user-initiated (either manually activated or based on pre-set schedule) inspection routines. In cases where a machine fails abruptly, the robotic-based data collection system would not be able to respond sufficiently quickly to collect data, which may be valuable to indicate the cause(s) of machine malfunctions. In this situation, permanently installed sensors may be more appropriate. Additionally, as a real-time video link is used as the core of the visualisation mechanism, both the proposed systems (Panu, et al., 1999; Bellamine, et al., 2002) may exhibit performance drop over low speed Internet/network connections or during heavy Internet/network

traffic (of course it may also be argued that in the near future, with advances in network communication technologies, such problem may not be considered as an issue anymore).

In an effort to minimize the requirements for network communication bandwidth, Mile (Mile and Mehboob, 2002) proposed and demonstrated a JAVA3D web-based remote machine monitoring system. The system was proposed to facilitate real-time collaboration between maintenance personnel present at different locations. It allows maintenance personnel to remotely monitor machine operations via a JAVA3D-based virtual environment embedded in a web browser, without requiring a real-time video link. Figure 3.2 shows a view of the JAVA3D viewer of a prototype of the proposed web-based remote monitoring system. Equipment operational data was acquired directly from equipment controllers via a special purpose server component, which then transferred the acquired data over the Internet to remote clients. On the client side, the received data was used to update an animated 3D virtual model displayed in a JAVA3D-based virtual environment. In general, the work has demonstrated how a 3D-based virtual environment, when integrated with Internet/network technologies, could be used to create a remote virtual maintenance collaborative environment. However, there are various issues, which have not been addressed in the work. It may be argued that the real-time performance claimed by the author may become an issue in cases involving complex equipment systems and where network bandwidth is limited. Note that in the demonstration, the author has only experimented with an over-simplified machine system (which was only a 2-axis motorized mechanism).

From another perspective, it may also be argued that for maintenance support purposes, continuous and real-time transfer of equipment operational data may not be necessary. It would be more appropriate to transfer data only when it is necessary. For example, when equipment fails abruptly, it may be more useful to first log equipment operational data (automatically) into a temporary buffer. The data in the buffer may then be transferred in batches (offline, i.e. after the failure event), when requested by remote experts. Secondly, the work did not address issues related to data management and visualisation for complex equipment systems. As the virtual model is stored in a

database located at the server site, this implies the need to download the model at the beginning of each remote monitoring session. It may be more efficient if a copy of the model could be stored at a location local to machine experts. Thirdly, the proposed system architecture was focused mainly on the visualization aspects of the system. There was a lack of integration with other maintenance-support-tools/strategies. Such integration is important for the system to be efficient, particularly, for cases involving complex new generation manufacturing systems.

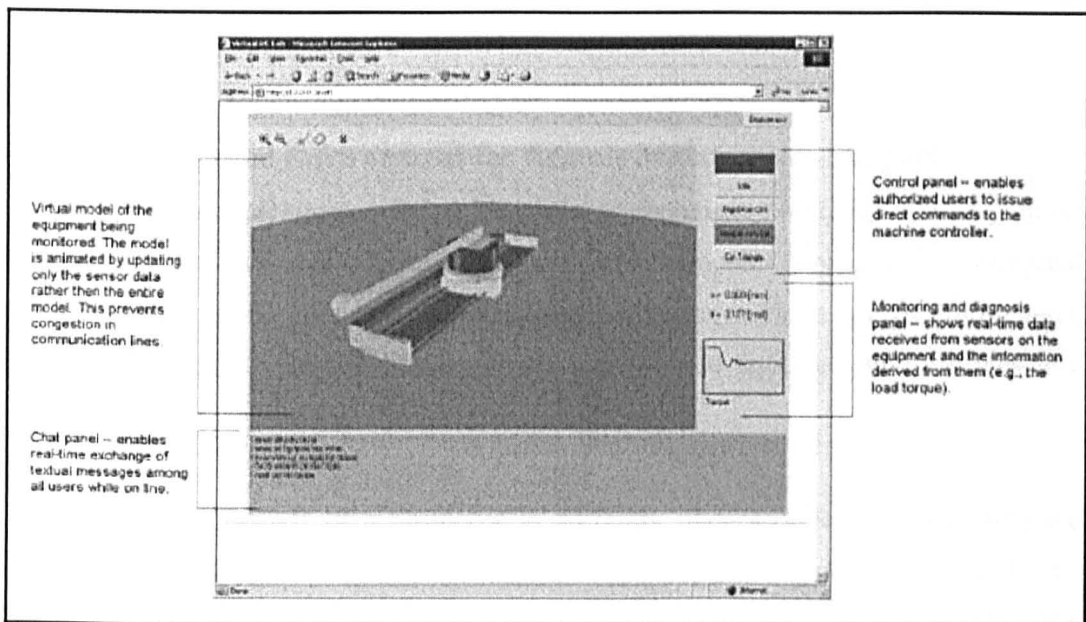


Fig. 3.2 JAVA3D web-based visualisation (Courtesy of Mile and Mehboob, 2002)

The literature review has revealed various unexplored potential of 3D virtual technology, in particular in terms of how it could be integrated with existing intelligent/ automated maintenance support strategies/technologies/tools. It is expected that such integration has the potential for further improving the cost-effectiveness and efficiency of existing remote machine service support for new generation manufacturing systems. The following section presents a review of an industry-based project – MASSIVE, aimed at exploring some of the potential.



## **3.6 Integration of 3D Virtual Engineering Tools with the Machine Maintenance Support and Machine Control System**

### **3.6.1 Introduction – MASSIVE**

Machine Service Support using Innovative Virtual Engineering (MASSIVE), is an industry-based Swedish project currently underway at the University of Skövde, Sweden, in collaboration with a number of major Swedish industrial companies (AP&T, DELFOi, Euromation, Volvo Cars and Volvo Powertrain) (Ng, et al., 2004). The project is focused on the use of virtual engineering tools for improving current remote machine maintenance support strategies.

### **3.6.2 An Integrated Environment for Remote Maintenance Support**

A reference architecture for an integrated environment – Machine Service Support System (MSSS), as shown in figure 3.3, has been developed. It proposes a conceptual framework that tightly integrates virtual engineering tools (machine system simulations), machine controllers (real and simulated) and model-based fault detection schemes in a network/Internet framework.

The development of a prototype is currently underway for demonstrating the feasibility of the proposed framework. For the acquisition of equipment operational data, the prototype uses the OLE for Process Control (OPC) technology (OPC, 2003). The OPC simplifies the acquisition of discrete-event and continuous data with low change rate (<100Hz). It allows data to be acquired directly from PLCs/soft-logic controllers or from the fieldbus. For the acquisition of operational data for parameters with high change rates, dedicated sensory and high-speed data-acquisition devices will be required. The data acquisition system has been designed to be remotely configurable. It allows users to remotely configure various parameters such as to select machine process variables, discrete-event signals, time intervals, sampling rates etc. All communications between the MSSS and the remote machine site is done via XML web-services provided by a web-service server located at the machine site. Currently, the web services are being

developed using Microsoft's ASP.NET technology. The MSSS provides a common user interface for both local and remote experts/engineers.

For continuous remote monitoring or in case of a machine fault/failure (breakdown), the MSSS provides tools for users to use historical data logged in a database to carry out "playback" in a 3D virtual environment. This allows users to investigate the recent history and current status of a remote equipment system. Simultaneously, users can access available reference dynamics models, which are used to simulate the operation of a machine system using archived historical data. Both output data generated by a simulator and historical data can be visualised and compared using various data analysis tools/techniques. The reference framework also proposes the integration of the MSSS with a control system software logic verification, testing and simulation environment, and tools to facilitate remote installation of control system software components into a target controller.

### **3.6.3 Initial Experimentation and Motivation for an Extended Study**

Initial experimentation based on a test bed in Euromation, Sweden, has demonstrated the feasibility of the proposed approach. The outcomes of the initial experimentation have motivated this research study (at the Mechatronics Research Centre, De Montfort University, UK). The aim of this extended study is to further explore the potential of a 3D-based virtual environment for allowing it to be used for extending the range of machine support services, and the integration of extended service support functions with conventional maintenance support functions.

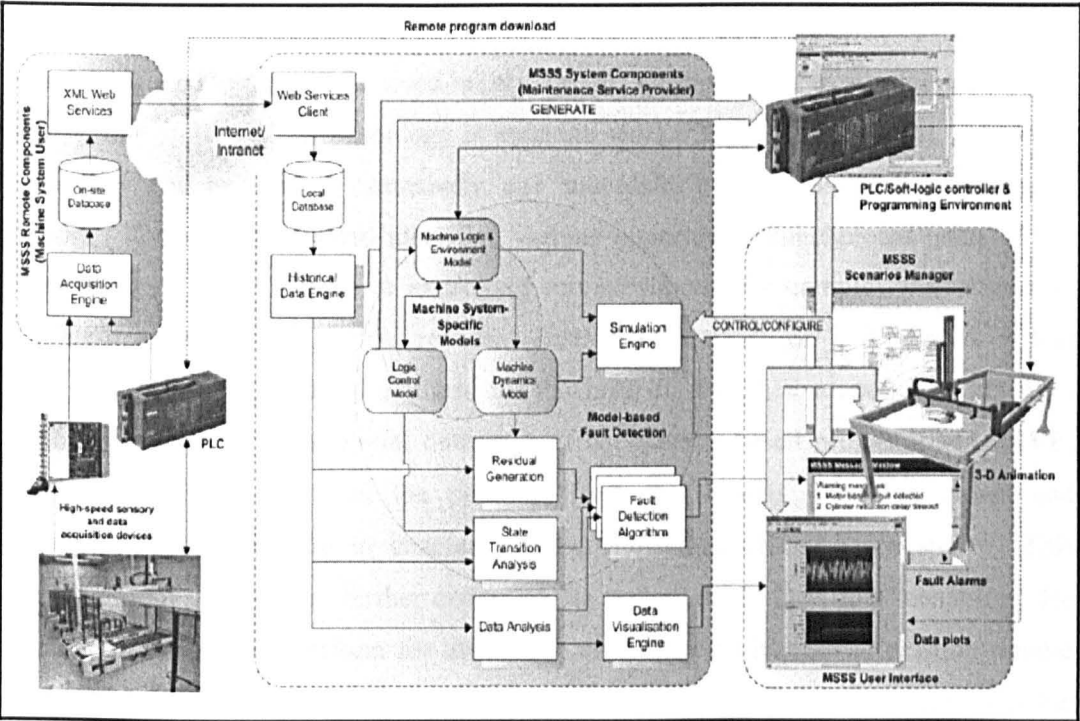


Fig. 3.3 Machine Service Support System (Courtesy of Ng, et al., 2004)

### **3.7 Chapter Summary**

This chapter has presented a review of various current developments and applications of 3D virtual technology in machine service support. In general, 3D virtual technology has been used extensively and successfully in the area of maintenance support. The review has also identified various opportunities/unexplored areas of 3D virtual technology in relation to improving service support for complex manufacturing systems. In particular, it has revealed that, the potential of a 3D-based virtual environment as an integration platform for machine maintenance support, has not been sufficiently explored. The initial outcomes of an industry-based project – MASSIVE, initiated to explore some of the potential (and the various identified issues and opportunities, as presented in chapter 2) have motivated this research study. This extended study is aimed at further exploring the potential of 3D virtual technology for creating an integration platform for improving the cost-effectiveness of existing remote machine service support strategies for new generation manufacturing systems and the extension of conventional maintenance support functions for providing more comprehensive service support for new generation manufacturing systems. It is expected that such an integration platform would allow various existing machine service support strategies/tools to be leveraged more cost-effectively. The following chapter presents a detailed description of a machine service support strategy, taking advantage of 3D virtual technology, proposed for improving the service support for new generation manufacturing systems.

## **Chapter 4**

# **An Advanced Machine Service Support Strategy**

### **4.1 Introduction**

This chapter presents a detailed description of a proposed advanced machine service support strategy for new generation manufacturing systems. A corresponding (proposed) service support system (i.e. the support tool) to support the strategy is presented in chapter 5. First, section 4.2 presents a set of main requirements identified for the proposed service support strategy. Next, section 4.3 presents a detailed discussion of a process model of the proposed strategy, followed by the description of five service support scenarios illustrating the main ideas of the proposed strategy. The last section (section 4.4) presents a summary of the chapter.

### **4.2 Requirements**

#### **4.2.1 Introduction**

The strategy should facilitate the implementation of cost-effective, efficient and comprehensive advanced service support for new generation manufacturing systems. Specifically, it must be capable of providing the following support services:

##### **(1) Maintenance Support**

It must facilitate machine builders/suppliers in providing cost-effective and efficient machine maintenance support for the equipment they supply. The main aims of the support are: (1) to facilitate the maintenance of the equipment's *physical life*, and (2) to facilitate the continuous improvement of equipment during its in-service life. It should minimize the number of site visits and shorten the time-scale for completing an onsite maintenance service. The maintenance support functions should include the following: remote fault detection, diagnostics, prognostics, maintenance action decision support, remote re-configuration of the control system (both control parameters and control system software components) and onsite maintenance services.

##### **(2) Extended Service Support**

It must facilitate machine builders/suppliers in providing cost-effective and efficient equipment re-configuration, upgrade and expansion support for the equipment they supply. The main aim of these support functions is to support customers to respond more rapidly and cost-effectively to market changes, by facilitating in-service changes to their manufacturing systems for meeting new production requirements. The support is also required to minimize environmental impact by prolonging the service life of equipment (by encouraging the re-use of existing equipment's components) and thus, minimizing wastage. The support must include a wide range of support services, ranging from the minor remote re-configuration of operational/control parameters to major hardware/software re-configuration/upgrade/expansion operations, which may involve major adjustments/modifications to the original equipment.

#### **4.2.2 Functional Requirements**

In order to fulfil the aforementioned operational requirements, the following functional requirements have been identified:

##### **(1) Remote Collaboration**

It must facilitate the collaboration between remote experts/engineers and local/site engineers/technicians whenever necessary.

##### **(2) Efficient Onsite and Offsite Activity Coordination**

It should facilitate the coordination of onsite and offsite support activities. It should leverage existing automated/intelligent maintenance support tools, which should be distributed to equipment sites (e.g. by embedding them into an equipment system), whenever appropriate. It should also allow remote experts/engineers to coordinate their activities with those of automated maintenance support tools (both onsite and offsite). For achieving cost-effective and efficient extended service support, it should facilitate the concurrent execution and synchronization/coordination of re-configuration/upgrade/expansion operations for the hardware element (performed onsite), and the software element (performed offsite).

##### **(3) Efficient Operation Feedback**

It must include an efficient feedback strategy to facilitate the continuous acquisition, visualization, analysis and re-use of equipment operational and maintenance-related data/information. It must allow remote experts/engineers to access a comprehensive set of data/information already available in an equipment system such as data/information generated by installed automated maintenance-support-tools and that used/generated by the control system. It must also facilitate the acquisition of additional data/information if it is not already available in the equipment system.

**(4) Efficient Automated Maintenance-support-tool Support**

It must facilitate remote experts/engineers in developing, implementing and integrating automated maintenance-support-tools into an equipment system. It must also facilitate the continuous remote improvement and optimization of the support tools. Accordingly, it must include the following: (1) a strategy for the continuous assessment of the performance of automated maintenance-support-tools, (2) a strategy for the development/refinement of the support tools, (3) a strategy and mechanism to facilitate the management of the support tools and (4) a strategy to facilitate the upgrade/re-configuration of the support tools.

**(5) Remote Re-configuration/Upgrade**

It must allow or facilitate remote experts/engineers in performing re-configuration/upgrade of the software components of the equipment they supply. This process must be done in coordination with the machine user's activities. Accordingly, an appropriate synchronization strategy must be provided.

**(6) Efficient Design Evaluation and Feedback**

It must facilitate the re-use of all acquired data/information and archived reference for the assessment of equipment's performance, which can be used to provide feedback for the evaluation and improvement of equipment design and for the improvement of existing support tools such as maintenance-support-tools.

**(7) Efficient Data/Information Archiving**

It must facilitate the archiving and re-use of all data/information relevant to the design, operations, maintenance and support activities of existing equipment.

### **4.2.3 Non-functional Requirements**

#### **(1) Flexible and Cost-effective Data Acquisition**

The data acquisition strategy should leverage the built-in capabilities of the control system such as data/information logging capabilities. It should minimize the need for additional sensors (and associated signal conditioning/data acquisition components). To facilitate the data/information acquisition process, a strategy to facilitate either the installation/removal of new/redundant data acquisition tools must be put in place. In addition, a strategy for the acquisition of additional data/information (which cannot be acquired cost-effectively via automated acquisition tools), via the assistance of the machine user must also be provided.

#### **(2) Efficient, Flexible and Fault Tolerant Communication**

In order to achieve efficient communication, it should leverage existing information and communication technologies/infrastructures, specifically, network/Internet-based technologies. It should take advantage of different technologies for the communication of data/information of different types and priorities. Appropriate 'back-up' strategies must be put in place to cater for communication uncertainties such as network/Internet disruptions.

#### **(3) Communication Security**

In the aspect of communication security, it should leverage the available security strategies/mechanisms of existing information and communication technologies/infrastructures. In addition, a systematic strategy to facilitate the integration of new strategies/technologies must be provided.

#### **(4) Operational Safety and Security**

The machine user must retain the right to grant/refuse permission for allowing remote experts/engineers to perform any remote equipment re-configuration/upgrade operations. Such remote operations must under no circumstances disrupt the normal operation of equipment. Remote experts/engineers must under no circumstances be given the right to direct remote control of equipment. If such a remote control operation is absolutely necessary, remote experts/engineers should only be given permission for performing an indirect remote control operation.



The term 'indirect' implies that local engineers/technicians retain the right to decide when/whether a requested operation (made by remote experts/engineers) should be executed.

**(5) Flexible and Scalable Strategy**

It must be flexible and scalable to cater for uncertainties such as in-service changes in equipment, and to facilitate the integration of new maintenance support strategies/technologies/tools. It should facilitate the re-use and re-configuration (i.e. re-organization) of existing support tools in case of equipment re-configuration/upgrade/expansion.

## 4.3 Conceptual Framework

### 4.3.1 Introduction

The proposed advanced remote service support strategy is based on extending the basic ideas of conventional remote maintenance support strategies (as illustrated in figure 4.1, see figure 4.2 for the proposed strategy) using an integrated 3D-based virtual environment as the integration platform. The proposed system advocates a strategy to support the machine builder/supplier in the shift from the conventional ‘**product-based business model**’ to the more sustainable ‘**service-based business model**’ (Takata, et al., 2004). The limitations of conventional remote maintenance support strategies in respect of providing more cost-effective and comprehensive service support for new generation manufacturing systems, have motivated the author to conduct research into the potential of the following enhancement and extensions to conventional remote maintenance support strategies:

- (1) Integration of remote support functions for supporting the development, testing, assessment and installation/re-configuration/upgrade of automated/intelligent maintenance-support-tools, to allow the maintenance-support-tools to be leveraged more cost-effectively. These support functions are necessary due to the complexity of implementing automated maintenance-support-tools for complex manufacturing systems. The complexity of implementing automated maintenance-support-tools has been highlighted by a number of researchers (Carl, et al., 2004, Hvass and Tesar, 2004).
- (2) Integration of a remote design feedback and re-configuration support mechanism for facilitating continuous improvement and optimisation of new generation manufacturing systems during their in service life, in the following aspects: (1) equipment performance improvement and optimisation via re-configuration of control parameters and, upgrade of control system software components and (2) equipment design improvement and optimisation to alleviate/remove design deficiencies/faults, eradicate/minimize maintenance requirements and to improve service-ability, in addition to improvement in terms of functionality and performance. The need for an efficient strategy for supporting in-service

equipment improvement and optimisation has been highlighted by Takata (Takata, et al., 2004).

- (3) Integration of extended service support functions for supporting in-service re-configuration/upgrade/expansion for new generation manufacturing systems. The integration of this strategy is essential to maintaining/prolonging the functional life of new generation manufacturing systems. The integration of these functions are motivated by the need for more comprehensive service support as highlighted by a number of researchers (Takata, et al., 2004; Tomiyama, 1999; Wilfried and Graupner, 2002).

The idea of using a 3D-based virtual environment as an integration platform for supporting the aforementioned strategies was motivated by the following:

- (1) Successful application of 3D virtual technology in various engineering areas (design, development, operation and maintenance).
- (2) Limitations of the remote visualisation capability of conventional remote maintenance support systems, especially in respect of their application for supporting complex new generation manufacturing systems.
- (3) A number of research efforts related to the application of 3D virtual environments as virtual collaborative platforms for remote maintenance support have indicated potential benefits (Panu, et al., 1999; Bellamine, et al., 2002; Mile and Mehboob, 2002). The initial outcomes of the MASSIVE project (Ng, et al., 2004), have demonstrated the feasibility of integrating 3D virtual technology with the equipment control system and various fault detection tools, in a network/Internet framework, for improving equipment remote monitoring and diagnostics. For supporting the proposed advanced remote service support strategy for complex new generation manufacturing systems, a number of refinements, enhancement and extensions to conventional remote maintenance support systems (as illustrated in figure 2.4, see page 26) have been proposed (See chapter 5 for details.).

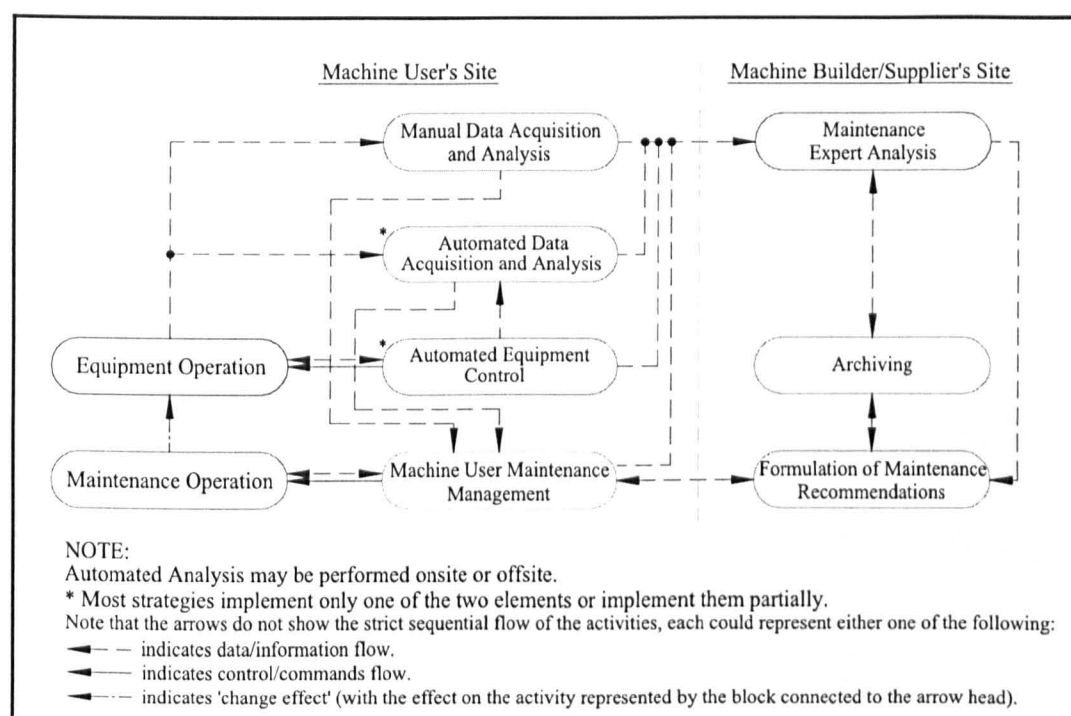


Fig. 4.1 Typical activity flow of conventional remote maintenance support strategies

Figure 4.2 shows an 'Activity Relationship Diagram' (which depicts a simplified top-level process model) of the proposed service support strategy. It should be noted that the figure does not suggest a sequential flow of the various component activities. Instead, it only shows the relationships between the activities (most of which are concurrent). In this context, the term 'relationships' refers to the coordination and interactions between the various component activities such as data/information/commands/controls flows. With reference to the figure, it can be seen that the proposed approach advocates concurrent execution of various service support activities, tightly integrated with onsite automated maintenance support activities and in close coordination with the machine user's activities.

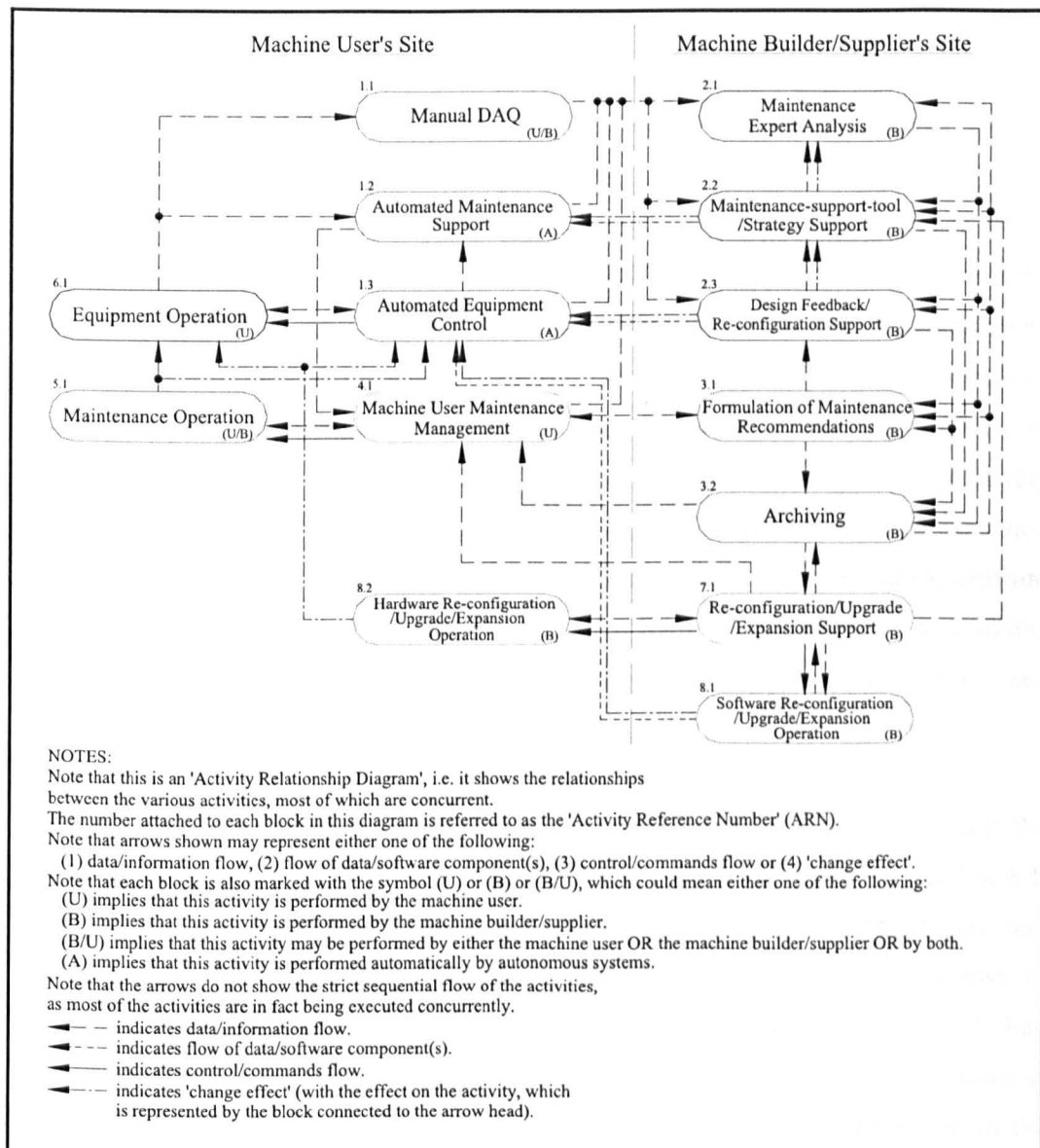


Fig. 4.2 Proposed advanced machine service support strategy

To streamline the maintenance support process, the approach advocates a systematic strategy to facilitate continuous in-service improvement and optimisation of the remote maintenance support process via: (1) integration with the onsite **Automated Maintenance Support** activity (block 1.2 of figure 4.2) (which is performed with the aid of automated maintenance-support-tools), (2) integration with the **Maintenance-support-tool/Strategy Support** activity (block 2.2 of figure 4.2) to streamline the

implementation of and support for automated maintenance-support-tools, (3) integration with the **Design Feedback and Re-configuration Support** activity (block 2.3 of figure 4.2) to facilitate long term improvement and optimisation of equipment's performance, reliability and maintainability/serviceability.

Additionally, in order to streamline extended service support activities, the approach proposes: (1) an integrated long-term strategy, facilitating the acquisition, archiving and re-use of equipment design, operational and maintenance-related knowledge/experience (via the **Archiving** activity – block 3.2 of figure 4.2), to streamline the equipment re-configuration/upgrade/expansion design and planning process, in conjunction with (2) a strategy, advocating coordinated concurrent execution of multiple extended service support activities (coordinated via the **Re-configuration/Upgrade/Expansion Support** activity – block 7.1 of figure 4.2), both onsite and offsite, to streamline the equipment re-configuration/upgrade/expansion development and implementation process.

For ease of explanation, the following sub-sections (4.3.2 to 4.3.13) present the roles of each component activity and its sub-activities. This is followed by section 4.4, where various support scenarios are presented, for illustrating the relationships and interactions between the component activities and their activity flows. For ease of understanding, the reader may want to first skim through sub-section 4.3.2 to 4.3.13, then continue to section 4.4. The reader may then refer back to the relevant sub-sections in section 4.3 from time to time for more information on each component activity, as the corresponding term that refers to it, is encountered in the text (in section 4.4). To avoid confusion, please read through the notes section of figure 4.2 for information on the notations used, before proceeding to the next sub-section.

### 4.3.2 Automated Maintenance Support

The **Automated Maintenance Support** activity (block 1.2 of figure 4.2) is performed to improve the efficiency of remote maintenance support by minimising the workloads of remote machine experts (humans). This activity is performed with the aid

of a set of modular automated maintenance-support-tools, which are embedded in the equipment system. It is performed (triggered) either automatically (or partially automatically with minimum human intervention) according to pre-set configurations/schedules or on-demand based on the request of remote experts/engineers or machine users. It encompasses a series of activities, such as automated data acquisition, monitoring, health assessment, diagnostics, prognostics, decision support etc. Its output is transferred automatically/on-demand to remote site(s) (for machine expert analysis) or local maintenance management systems (used by the machine user for maintenance planning). Ideally, the output of this activity should provide sufficient and reliable information on which well-informed maintenance decision(s) could be made by the machine user, without the need for additional support from remote machine experts. In cases where the output doesn't provide sufficient information or there are uncertainties in the information provided, requests for remote support would be initiated (typically, automatically, or, on-demand by the machine user). It should be noted that in practice, the development of the automated support tools for this activity is a resource consuming and an ongoing process. Typically, during the initial equipment operational phase, only a rudimentary set of support tools is available. Ideally, the tools would be continuously improved and new tools being added during the operational phase of equipment (via the **Maintenance-support-tool/Strategy Support** activity - block 2.2 of figure 4.2, which will be described in sub-section 4.3.5). To facilitate this process, a remote re-configuration/upgrade mechanism for the support tools is provided.

### 4.3.3 Manual Data Acquisition (Manual DAQ)

In order to cater for various uncertainties in **Automated Maintenance Support** activity (described in sub-section 4.3.2), a complementary activity - **Manual DAQ** (block 1.1 of figure 4.2.) is performed. It is required for the acquisition of additional data/information for which no permanent sensor is installed, due to factors such as design constraints, design deficiencies etc. It is also applicable to situations involving the acquisition of data/information, which is qualitative in nature such as surface condition (colour, dirt, scratch, crack etc), structural condition (fastener looseness, missing parts, fracture etc) etc. In practice, these classes of data/information may be captured more

cost-effectively manually with the aid of portable acquisition/inspection tools such as portable visual inspection devices etc. As the term implies, it requires additional data acquisition activities to be performed onsite, which may be performed by the machine user's engineers/technicians or by the machine builder's engineers/experts (via a site visit), typically, with the aid of portable data acquisition tools. The main output of the process is, typically, low-level data, either in its raw form or pre-processed forms such as the filtered form, the frequency spectrum of original data etc. The output is transferred on-demand to remote site(s) as supplementary data/information, in addition to data/information acquired via the **Automated Maintenance Support** activity (block 1.2 of figure 4.2), to facilitate the remote expert analysis process.

#### 4.3.4 Maintenance Expert Analysis

The **Maintenance Expert Analysis** activity (block 2.1 of figure 4.2) is the main activity performed by remote machine experts in case of equipment malfunctions, for the purpose of identifying the sources/root causes of the malfunctions. It may also be performed as a routine for the collection of operational data, which would be used for supporting the development of maintenance-support-tools and for design feedback assessment. The input for this activity may include the following data/information: (1) all data/information collected/produced by the **Manual DAQ** and **Automated Maintenance Support** activity (block 1.1 and 1.2 of figure 3.1), (2) equipment control and feedback data (from the **Automated Equipment Control** activity – block 1.3 of figure 4.2), and (3) machine users' historical maintenance records (from the **Machine User Maintenance Management** activity – block 1.4 of figure 4.2). In general, this is a very resource-consuming and complex process requiring active involvement of remote experts, typically involving intensive analysis of large quantities of acquired/archived historical data/information. For this reason, various maintenance-support-tools are provided (provided by the **Maintenance-support-tool/Strategy Support** activity – block 2.2 of figure 4.2), which may be categorized into the following two main groups: (1) automated maintenance-support-tools, which are embedded in the equipment system, such as automated fault detection and diagnostic tools, and (2) partially-automated analysis support tools, provided via a set of support tools libraries located at the machine



builder's site(s), such as data pre-processing, transformation, analysis, visualization and decision support tools. Ideally, the support tools would be continuously improved, optimized and enhanced with new tools during the in-service life of equipment (via the **Maintenance-support-tool/Strategy Support** activity - block 2.2 of figure 4.2, which will be described in sub-section 4.2.5). The output of the **Maintenance Expert Analysis** activity would contribute, mainly, to the **Formulation of Maintenance Recommendations** activity (block 3.1 of figure 4.2), which in turn makes use of the data/information for formulating maintenance recommendations to support the machine user's maintenance activities. Additionally, its (the **Maintenance Expert Analysis's**) output would also provide input for: (1) the **Maintenance-support-tool/Strategy Support** activity (block 2.2 of figure 4.2) and (2) the **Design Feedback Analysis/Re-configuration** activity (block 2.3 of figure 4.2) and (3) the **Archiving** activity (block 3.2 of figure 4.2).

#### 4.3.5 Maintenance-support-tool/Strategy Support

The **Maintenance-support-tool/Strategy Support** activity (block 2.2 of figure 4.2) is performed to provide support for the **Automated Maintenance Support** activity (described in sub-section 4.3.2) and the **Maintenance Expert Analysis** activity (block 2.1 of figure 4.2). The main idea is to facilitate, in the long run, systematic delegation of service support tasks from remote experts to more autonomous maintenance-support-tools/systems. For this purpose, the activity encompasses a series of activities to provide support for maintenance-support-tools: (1) maintenance-support-tools feedback analysis, for the assessment of performance of the tools, (2) improvement and optimization of existing support tools, (3) development and testing of new tools, and (4) re-configuration/upgrade/addition of maintenance-support-tools. Due to the probabilistic nature of maintenance support process, the series of activities is essentially an iterative process involving intensive data acquisition and analysis for the purpose of establishing a basic knowledge base for understanding equipment fault behaviours. The knowledge base would then serve as reference for the development and improvement of existing/new maintenance-support-tools/strategies. In general, newly developed maintenance-support-tools would need to undergo continuous test, performance assessment, refinement and

verification, which would be performed by remote machine experts. Once the required level of performance is reached, the support tools would then be installed (remotely) into the equipment system. For this purpose, a remote re-configuration/upgrade mechanism for the support tools is provided. Ideally, once installed into the equipment system, the automated support tools should then be able to function autonomously (with minimum human intervention), providing reliable and comprehensive information feedback (to either machine users or machine builders/suppliers or service providers), effectively, streamlining the overall support process and reducing human workloads. In practice, however, the continuous support for the tools would be required to allow the continuous improvement and optimisation of the support tools.

#### **4.3.6 Design Feedback and Re-configuration Support**

The main purpose of this activity is to facilitate the implementation of a long-term maintenance optimisation strategy (based on concepts such as Design Out Maintenance and Self-maintenance, refer to sub-section 2.2.5 and 2.2.6 for a brief review of the concepts), by providing a cost-effective design feedback mechanism, to facilitate the continuous improvement and optimization of equipment's operations and designs. This is achieved via the continuous assessment of equipment performance based on acquired/archived operational and maintenance-related data/information. The assessment outcomes would provide reference inputs for facilitating the formulation of potential improvement and optimization strategies for equipment. The series of activities may involve: (1) the identification of design flaws/design deficiencies (particularly if the flaws/deficiencies were linked with particular recurring equipment malfunctions) and the formulation of appropriate remedial actions for purposes such as to alleviate/remove design deficiencies/faults, to eradicate/minimize equipment maintenance requirements, to improve service-ability etc, (2) the identification of opportunities for the improvement and optimisation of equipment design/configuration in terms of performance and functionality, and the formulation of appropriate remedial actions, and (3) the identification of opportunities for improvement and optimisation of design support tools such as simulation tools/models etc. Ideally, the output of the activity would provide supplementary reference input for the **Formulation of Maintenance Recommendations**

activity (block 3.1 of figure 4.2), in addition to the output of the **Maintenance Expert Analysis** activity (block 2.1 of figure 4.2). In cases where the identified improvement strategies require only the re-configuration of the equipment software system, remote re-configuration operations would be performed (in coordination with the machine user's operations). Otherwise, onsite re-configuration operations would be required. Additionally, the output of this activity would also provide input for: (1) the **Maintenance-support-tool/Strategy Support** activity (block 2.2 of figure 4.2) and (2) the **Archiving** activity (block 3.2 of figure 4.2).

#### 4.3.7 Formulation of Maintenance Recommendations

The main purpose of the **Formulation of Maintenance Recommendations** activity (block 3.1 of figure 4.2) is to provide timely, reliable and comprehensive maintenance recommendations for the machine user to facilitate the maintenance planning process (which is a sub-activity of the **Machine User Maintenance Management** activity – block 4.1 of figure 4.2). The sources of data/information for this activity may include the following: (1) the output of the **Maintenance Expert Analysis** activity (block 2.1 of figure 4.2), (2) the output of the **Design Feedback Analysis/Re-configuration** activity (block 2.3 of figure 4.2) and (3) archived historical reference (the 'output' of the **Archiving** activity – block 3.2 of figure 4.2). The output (i.e. the recommendation(s)) of this activity is communicated to the machine user (the **Machine User Maintenance Management** activity) for further decision(s), which may involve further negotiation(s). The recommendation(s) may be based on one or more of the following maintenance approaches: (1) **Corrective Maintenance** (refer to sub-section 2.2.2 for a review of the concept) – to rectify/replace a malfunctioned part/component/sub-system, (2) **Preventive Maintenance** (both schedule-based and condition-based, refer to sub-section 2.2.3 and 2.2.4 for a review of the concepts) – to service/re-configure/replace a part/component/sub-system before it malfunctions or (3) **Design Out Maintenance** – for the re-design of a part/component/sub-system identified as a source or a potential source of equipment malfunction(s).

#### 4.3.8 Archiving

The **Archiving** activity (block 3.2 of figure 4.2) is performed as a mechanism for systematic acquisition, storage and retrieval of all data/information (knowledge and experience) relevant to the service support process. The following data/information may be archived: (1) the output of the **Maintenance Expert Analysis** activity (block 2.1 of figure 4.2), (2) the output of the **Maintenance-support-tool/Strategy Support** activity (block 2.1 of figure 4.2), (3) the output of the **Design Feedback Analysis/Re-configuration** activity (block 2.3 of figure 4.2) and (4) all feedback from the machine user/assessment outcomes of onsite operations. The archived historical data/information is, in turn, used as input for various support activities, which include: (1) the **Maintenance Expert Analysis** activity, (2) the **Maintenance-support-tool/Strategy Support** activity, (3) the **Design Feedback Analysis/Re-configuration** activity, (4) the **Re-configuration, Upgrade and Expansion Support** activity (block 7.1 of figure 4.2), (5) the **Machine User Maintenance Management** activity (block 4.1 of figure 4.2), and (6) other activities such as equipment design and development activities.

#### 4.3.9 Re-configuration, Upgrade and Expansion Support

The main purpose of the **Re-configuration, Upgrade and Expansion Support** activity (block 7.1 of figure 4.2) is to support the execution of equipment re-configuration, upgrade and expansion operations. Some of the main support functions are: (1) re-configuration/upgrade/expansion design, (2) operation planning, and (3) coordination for the following activities: hardware re-configuration/upgrade/expansion operations (via the **Hardware Re-configuration/Upgrade/Expansion Operation** – block 8.2 of figure 4.2), software re-configuration/upgrade/expansion operations (via the **Software Re-configuration, Upgrade and Expansion Support** activity – block 8.1 of figure 4.2), and maintenance-support-tool re-configuration operations (via the **Maintenance-support-tool/Strategy Support** activity (block 2.2 of figure 4.2).

#### 4.3.10 Software Re-configuration/Upgrade/Expansion Operation

The **Software Re-configuration/Upgrade/Expansion Operation** (block 8.1 of figure 4.2) is performed on the existing software component(s) of original equipment in

order to meet a new/modified set of operational requirements. The series of activities may consist of: the development of new software component(s) or the modification/upgrade/expansion of existing software component(s), testing and debugging, based on a 3D-based virtual prototype of the re-configured/upgrade/expanded equipment. Note that this activity is performed offsite, in conjunction with the **Hardware Re-configuration/Upgrade/Expansion Operation** (block 8.2 of figure 4.2), which is performed onsite. Ideally, this activity should be completed before the completion of the **Hardware Re-configuration/Upgrade/Expansion Operation**, allowing smoother (re-)commissioning of the re-configured/upgraded/expanded equipment.

#### **4.3.11 Hardware Re-configuration/Upgrade/Expansion Operation**

The **Hardware Re-configuration/Upgrade/Expansion Operation** (block 8.2 of figure 4.2) is performed concurrently with the corresponding operation on the software, as described in sub-section 4.3.10. The series of activities may consist of: the development of new hardware component(s) (which may require the re-design of existing component(s)), the modification/upgrade/expansion of existing components/sub-systems, onsite testing, troubleshooting and re-adjustment. Ideally, after the completion of this operation, the software for the newly re-configured/upgraded/expanded equipment should be ready for installation and (re-)commissioning.

#### **4.3.12 Machine User Maintenance Management**

The **Machine User Maintenance Management** activity (block 4.1 of figure 4.2) refers, generally, to a group of management activities performed by the machine user to manage and coordinate maintenance activities. In this context, it consists of the following main sub-activities: (1) maintenance planning, based mainly on the data/information provided by the **Automated Maintenance Support** activity and recommendations from the machine builder, (2) pre-arrangement such as scheduling, allocation of human resource, arrangement for getting necessary spare parts, tools etc, (3) maintenance work coordination, particularly if the maintenance work involves/performed by the machine builder and (4) maintenance work evaluation, feedback and archiving.

#### 4.3.13 Others

The **Maintenance Operation** activity (block 5.1 of figure 4.2) refers, generally, to a group of activities performed on equipment for the following purposes: (1) recovery of equipment operation after experiencing faults/failures (i.e. Corrective Maintenance), (2) service activities or re-adjustment/replacement of equipment component(s) reaching the end of their manufacturer-recommended service life (i.e. Time-based/Schedule-based Preventive Maintenance), (3) service activities or re-adjustment/replacement of equipment component(s) (perceived as) experiencing operation deviation(s)/degradation (i.e. Condition-based (Preventive) Maintenance) and (4) modifications to/replacement of equipment component(s), which have been perceived as the major sources of equipment malfunctions/problems (i.e. Design Out Maintenance). The **Automated Equipment Control** activity (block 1.3 of figure 4.2) refers, generally, to all equipment control activities, typically performed by a group of integrated intelligent controllers (typically requiring only a minimum level of human intervention). Lastly, the **Equipment Operation** (block 6.1 of figure 4.2) refers, generally, to the normal operations of equipment.

## **4.4 Service Support Scenarios**

### **4.4.1 Introduction**

This section (4.4) presents a discussion of five scenarios for illustrating how various service support functions are performed, based on the proposed strategy. First, sub-section 4.4.2 and 4.4.3 present two scenarios, illustrating how current maintenance support functions for new generation manufacturing systems could be streamlined via the proposed strategy. Next, sub-section 4.4.4 and 4.4.5 present two additional scenarios, illustrating how maintenance support functions could be further streamlined and optimised in the long term through continuous improvement and optimization of both the maintenance-support-tool and the equipment system. The last sub-section (4.4.6) presents an extended service support scenario for illustrating how additional service support functions in the form of equipment re-configuration/upgrade/expansion support could be provided. Before proceeding to sub-section 4.4.2, please note the following:

- (1) The activity flow diagrams shown in figure 4.3, 4.4 and 4.5 are based on the activity relationship diagram shown in figure 4.2.
- (2) The activity reference number (ARN – a set of dot-separated numbers (e.g. 1.1.1) attached to each block in figure 4.2 to 4.5) is used to correlate the various activities/sub-activities depicted in figure 4.3, 4.4 and 4.5 with those in figure 4.2.
- (3) For a block in figure 4.3/4.4/4.5 having a two-number ARN (e.g. 1.1), the represented activity corresponds exactly to an activity represented by a block in figure 4.2 having the same ARN. For example, a block in figure 4.3/4.4/4.5 having ARN 1.1 and a block in figure 4.2 having the same ARN (i.e. 1.1) are actually referring to the same activity.
- (4) For a block with a three-number ARN (e.g. 1.1.1) in figure 4.3/4.4/4.5, the represented activity is a sub-activity of the corresponding activity represented by a block in figure 4.2 having an ARN with the same first two numbers. For example, blocks with ARN 1.1.1 and 1.1.2 in figure 4.3/4.4/4.5 are sub-activities of an activity represented by a block in figure 4.1 having ARN 1.1.

4.4.2 Scenario 1: Diagnostics/Prognostics when equipment operation deviations/unexpected faults/failures are detected

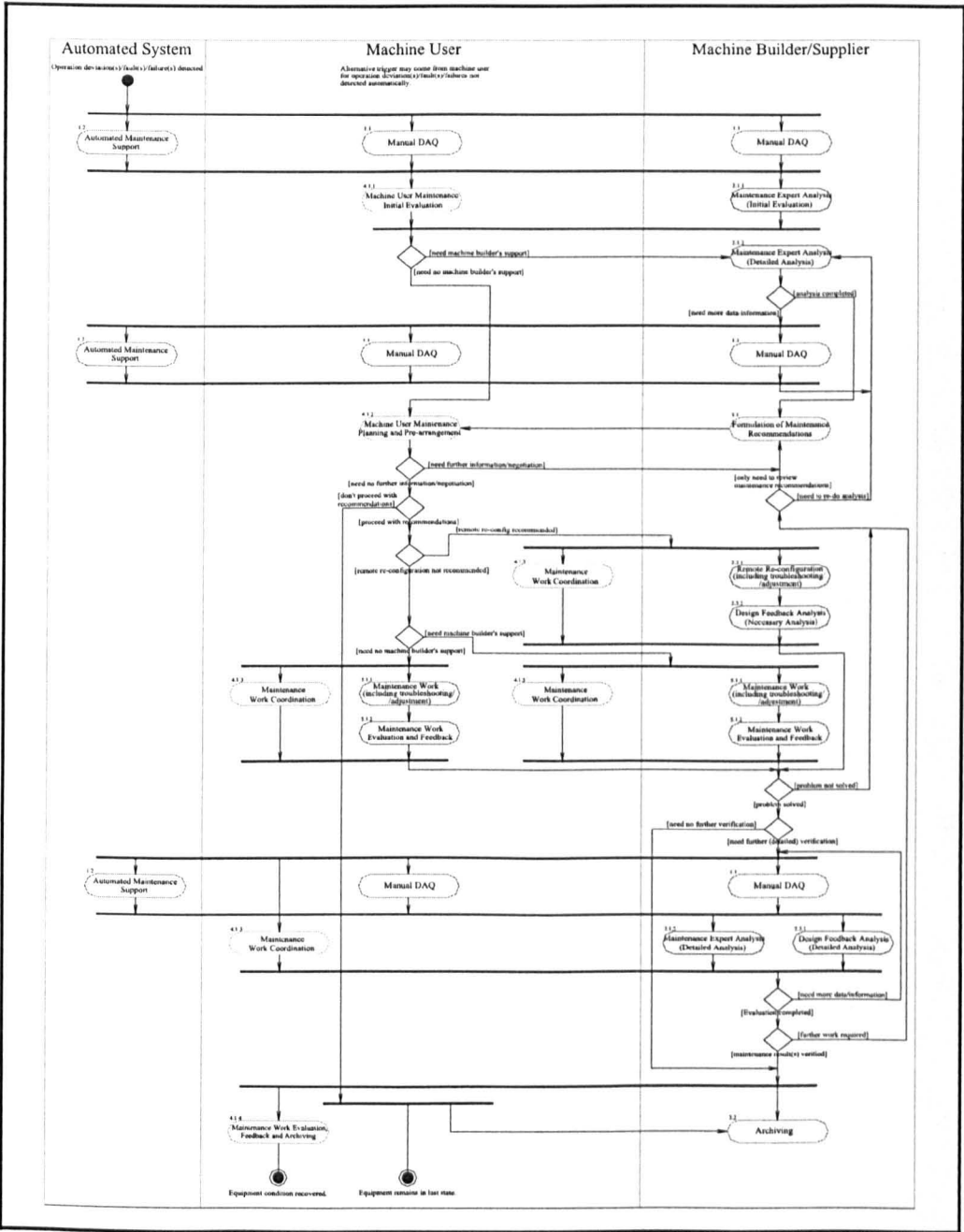
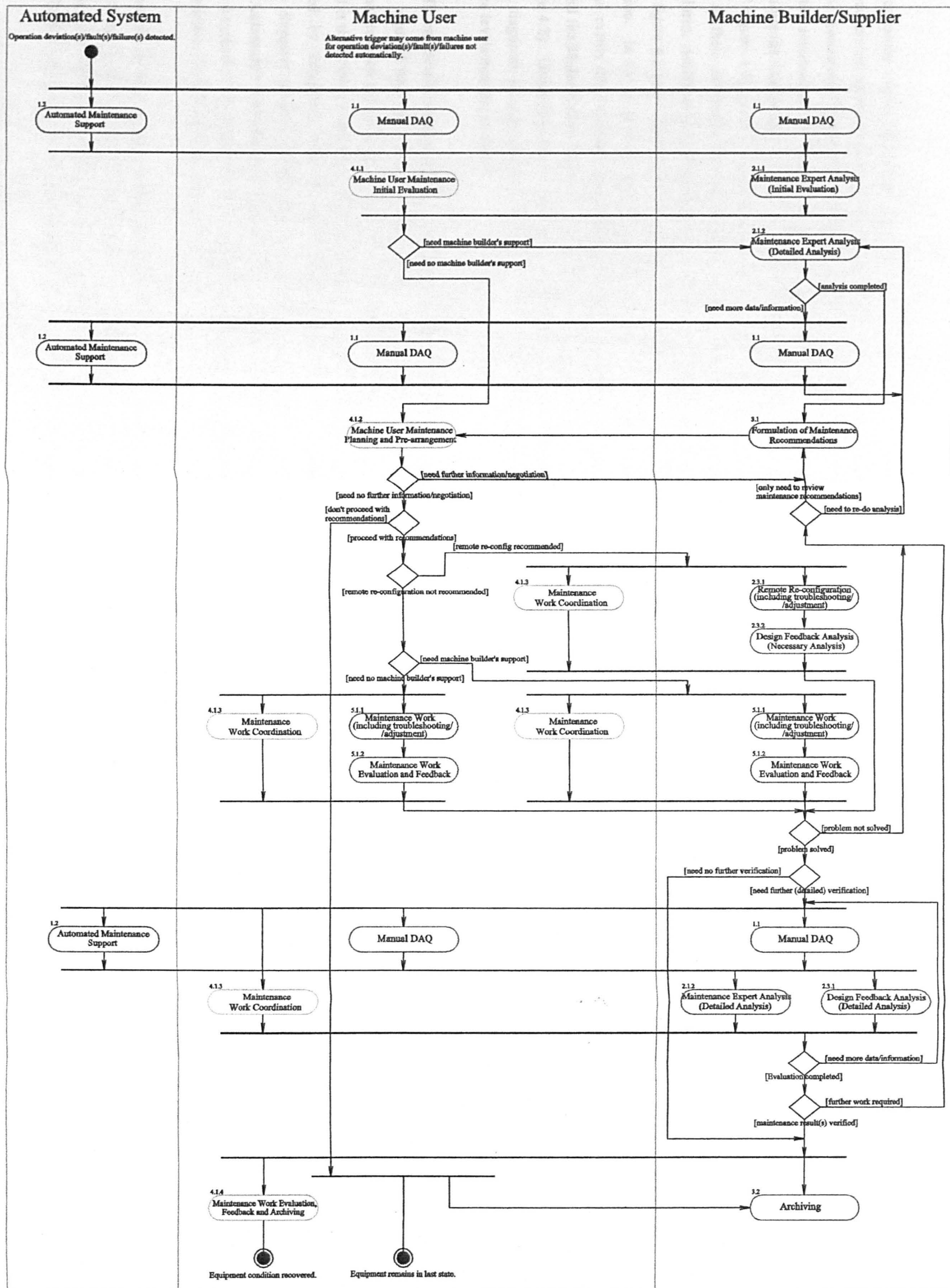


Fig. 4.3 Activity flow for scenario 1 (Please refer to the following page (A3) for an enlarged copy of this figure.)





This represents a typical maintenance support scenario where equipment exhibits operation deviations or experiences abrupt faults/failures. In this case (with reference to figure 4.2), the **Automated Maintenance Support** activity (block 1.2 of figure 4.2 and 4.1) is activated automatically to collect and analyse equipment operational data (from both the **Equipment Operation** – block 6.1 and **Automated Equipment Control** – block 1.3 of figure 4.1) prior to and after the events. Diagnostics (and possibly prognostics) is then performed to identify the possible sources of the detected deviations/failures. Additionally, the **Manual Data Acquisition (Manual DAQ)** activity (block 1.1 of figure 4.2 and 4.1) may also be performed for the acquisition of additional data/information. In the mean time, both the machine user and machine builder are notified of the events (the **Machine User Maintenance Initial Evaluation** activity – block 4.1.1 and the **Maintenance Expert Analysis (Initial Evaluation)** activity – block 2.1.1 of figure 4.2). Depending on the capability of available automated maintenance-support-tools, diagnostic (and possibly prognostic) outputs with different levels of details and confidence levels may be generated.

If sufficient details were available in the outputs, further diagnostics support would not be required from the machine builder. In this case, the machine user would proceed to maintenance planning (as presented in the fourth paragraph of this sub-section). This is the desirable case as it minimises the workloads of the machine builder. It is achieved by delegating most of the support activities to the **Automated Maintenance Support** activity, including the decision support function. To be effective, the **Automated Maintenance Support** activity has to be reliable. Sub-section 4.4.4 presents a scenario illustrating how the **Automated Maintenance Support** activity is supported remotely via the proposed service support strategy.

In cases where the required details/confidence-level is not available, support requests would be issued to the machine builder. Upon receiving the alarms and diagnostic/prognostic outputs, experts (humans) at the machine builder's site would perform verification of the outputs, and depending on the outcomes of the process,

further analysis may need to be performed. This activity is depicted as the **Maintenance Expert Analysis (Detailed Analysis)** activity (block 2.1.2 of figure 4.2). It may require the transfer of additional data/information from a central database (located at the machine user's site). The outputs of the **Maintenance Expert Analysis** activity are used as the main inputs for the **Formulation of Maintenance Recommendations** activity (block 3.1 of figure 4.2 and 4.1). Note that this activity would also make use of archived historical data/information relevant to the operations of the equipment system being monitored and that of other similar equipment systems/components. The outputs of the **Formulation of Maintenance Recommendations** activity would then be fed back to the machine user for decision on further actions (the **Machine User Maintenance Management** activity – block 4.1 of figure 4.1). In cases where the failures could be recovered via software re-configuration, the remote **Re-configuration Support** (block 2.3 of figure 4.1) would be recommended. In other cases where the failures involve the hardware, onsite maintenance operations would be recommended.

The machine user would then decide, plan and generate appropriate work orders (the **Machine User Maintenance Management** activity) for all necessary **Maintenance Operations** (represented by block 5.1.1 and 5.1.2 in figure 4.2). The **Maintenance Operations** may be performed, either: (1) by the machine user based on information provided by the machine builder or, (2) by the machine builder onsite (with or without the assistance of the machine user), or by the machine builder offsite via the remote **Re-configuration Support** activity (represented by block 2.3.1 and 2.3.2 in figure 4.2). Further verification of the effectiveness of the maintenance recommendations may need to be performed on completion of the maintenance operations. Once verified, all data/information relevant to the process would then be stored into a reference database (the **Archiving** activity - block 3.2 of figure 4.2 and 4.1), for future reference. However, if the maintenance operations failed to resolve the problems satisfactorily, the whole process would need to be repeated, as shown in the figure.

#### 4.4.3 Scenario 2: Periodic monitoring for condition-based preventive maintenance support

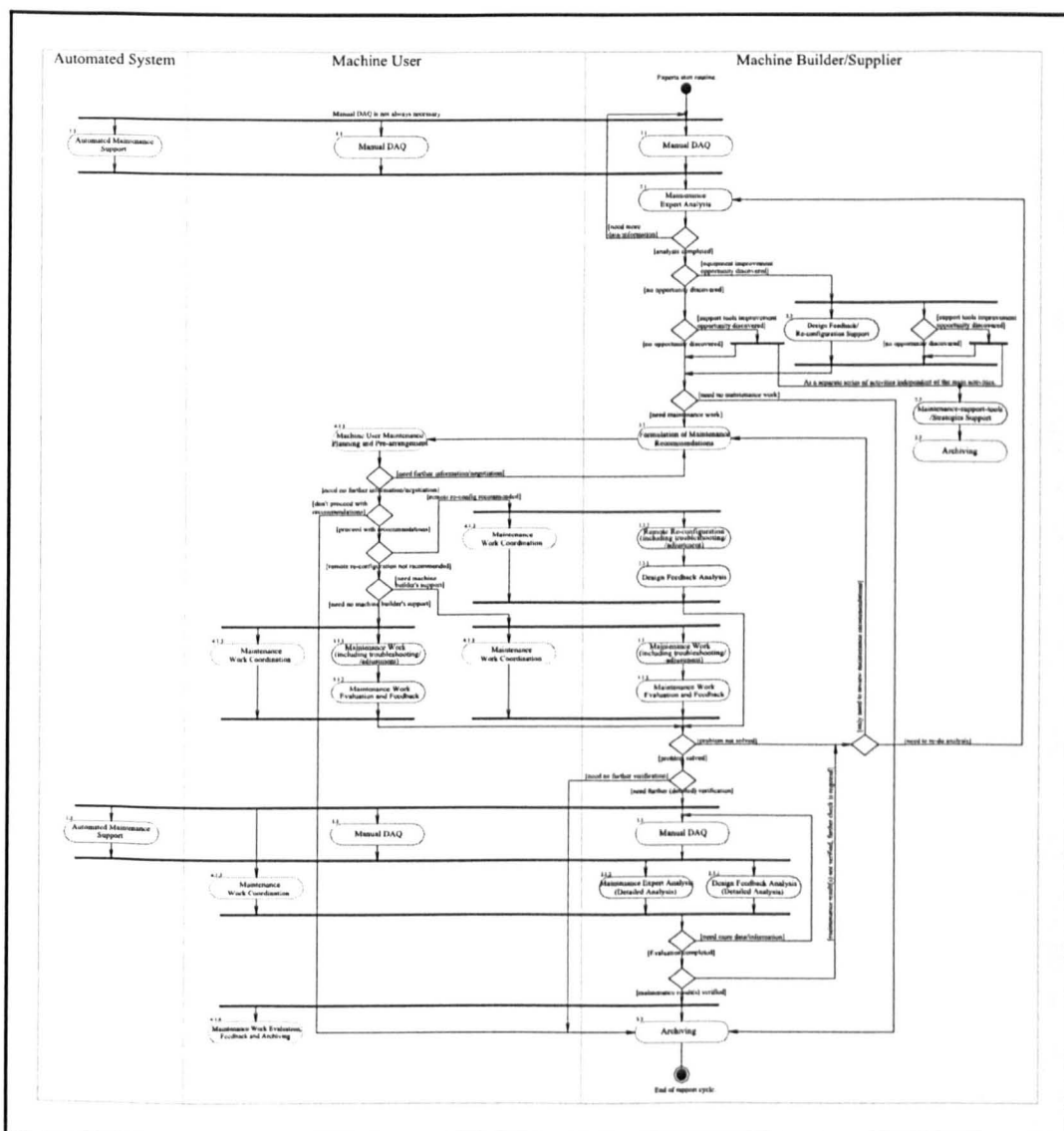


Fig. 4.4 Activity flow for scenario 2, 3 and 4 (*Please refer to the following page (A3) for an enlarged copy of this figure.*)

In general, this support process follows a similar activity flow described in scenario 1 (section 4.4.2). In this case (with reference to figure 4.3), however, equipment



operational and control data is acquired **routinely** (via the **Manual Data Acquisition (Manual DAQ)** – block 1.1 and **Automated Maintenance Support** activity – block 1.2 of figure 4.3 and 4.1, at either fixed or random intervals) and transmitted to the machine builder's site for analysis (the **Maintenance Expert Analysis** activity – block 2.1 of figure 4.3 and 4.1). The main purpose of the analysis is to gain an understanding of the operational behaviour of equipment, detection of faults/deviations, diagnostics and ultimately for the prediction of the future trends of equipment operations and remaining useful life (RUL). In addition, the outputs of the analysis (the **Maintenance Expert Analysis** activity) may also provide inputs for two additional support activities: (1) the **Maintenance-support-tool/strategy Support** activity (block 2.2 of figure 4.3 and 4.1, refer to sub-section 4.4.4 for further details) and (2) the **Design Feedback Analysis/Re-configuration Support** activity (block 2.3 of figure 4.3 and 4.1, refer to sub-section 4.4.5 for further details). The outputs of the three aforementioned activities would then be used for the formulation of necessary remedial/improvement/optimisation recommendations (the **Formulation of Maintenance Recommendations** activity – block 3.1 of figure 5.3 and 5.1). The subsequent steps follow similar procedures as described in scenario 1 (Refer to figure 4.3 for details.).

#### **4.4.4 Scenario 3: Maintenance-support-tool/Strategy support**

Concurrent with the series of activities described in both scenario 1 and 2 above, various activities may be performed for the continuous assessment, improvement and optimisation of existing maintenance-support-tools/strategies. New support tools may be developed, tested, verified and remotely installed into the equipment system. With reference to figure 4.1 and 4.3, the main activity in this case is the **Maintenance-support-tool/Strategy Support** activity (block 2.2 of figure 4.3 and 4.1). This activity makes use of data/information acquired during the support activities described in scenario 1 and 2 above and archived historical reference. Note that this support activity may also be initiated independently from the other support activities as suggested in figure 4.3. In this case, it makes use of mainly archived data/information (and remote acquisition of additional data/information may be initiated as necessary). The outputs of this activity (such as upgraded/new automated maintenance support tools), which would, ideally,

improve the effectiveness and efficiency (by reducing human workloads) of the **Maintenance Expert Analysis** activity. In practice, newly developed support tools would need to be tested and assessed, continuously. Once the support tools have been fully tested, they would be installed (remotely) (depicted as arrows pointing from block 2.2 to 1.2 in figure 4.1) into the equipment system, effectively allowing the partial delegation of support tasks from the remote expert to the equipment system. Ultimately, it is the aim of this support activity to automate most support tasks, in order to improve the overall efficiency of the service support process. Ideally, this would allow the **Machine User Maintenance Management** activity to directly make use of information provided by the **Automated Maintenance Support** activity for maintenance planning (depicted as arrows pointing from block 1.2 to block 4.1 in figure 4.1). All the relevant outputs of the process would also be archived - the **Archiving** activity (block 3.2 of figure 4.3 and 4.1), for future reference.

#### 4.4.5 Scenario 4: Design feedback

In conjunction with the activities described in scenario 3 above, additional support activities may also be performed for the verification of equipment design and the assessment of equipment performance. With reference to figure 4.1 and 4.3, the main activity, in this case, is the **Design Feedback Analysis/Re-configuration Support** activity (block 2.3 of figure 4.3 and 4.1). Similar to the **Maintenance-support-tool/Strategy Support** activity (block 2.2 of figure 4.3 and 4.1) (as described in scenario 3), this activity also makes use of data/information acquired during the support activities described in scenario 1 and 2, and archived historical reference. Note also that this activity may also be initiated independently of the other support activities as suggested in figure 4.3. In this case, it makes use of mainly archived data/information (and remote acquisition of additional data/information may be initiated as necessary). The outputs of the process may be used for the following purposes: (1) for the identification of design flaws/design deficiencies (particularly, if the flaws/deficiencies were linked with particular recurring equipment malfunctions) and the formulation of appropriate remedial actions, (2) for the identification of opportunity for the improvement and optimisation of equipment performance and the formulation of appropriate optimisation actions, (3) as

inputs for the improvement of design support tools such as simulation tools/models etc, and (4) as inputs for the **Maintenance-support-tool/ Strategy Support** activity, used for the optimisation of automated maintenance-support-tools, and (5) as inputs for a knowledge base, which would be used for other support activities (such as re-configuration, upgrade, expansion etc). Any formulated remedial/improvement/optimisation recommendations would need to be fed back following the similar procedures as described in scenario 1 (section 4.4.2). All the relevant outputs of the process would also be archived via the **Archiving** activity (block 3.2 of figure 4.3 and 4.1), for future reference.

#### **4.4.6 Scenario 5: Equipment re-configuration, upgrade and expansion support**

This represents an extended service support scenario, particularly relevant to the service support for new generation manufacturing systems. Note that this support activity is only concerned with cases requiring major re-configuration/upgrade/expansion operations, which would involve changes to the configuration of both the hardware and software elements of equipment, and in some cases, the original equipment design may need to be modified. After the completion of the customer interface (the **Communication** activity in figure 4.4) and requirements specification (the **Re-configuration/Upgrade/Expansion Requirements Specification** activity in figure 4.1) phase, the **Re-configuration/Upgrade/Expansion Design** (block 7.1.1 of figure 4.4) and **Operation Planning** (block 7.1.2 of figure 4.4) activity (as sub-activities of the **Re-configuration, Upgrade and Expansion Support** activity (block 7.1 of figure 4.1)) are performed. As shown in figure 4.4, these support activities would make use of archived historical operational and maintenance-related data/information (the 'outputs' of the **Archiving** activity, block 3.2 of figure 4.1), effectively leveraging all previous experience and knowledge acquired during all the other support activities described in scenario 1 to 4, above.



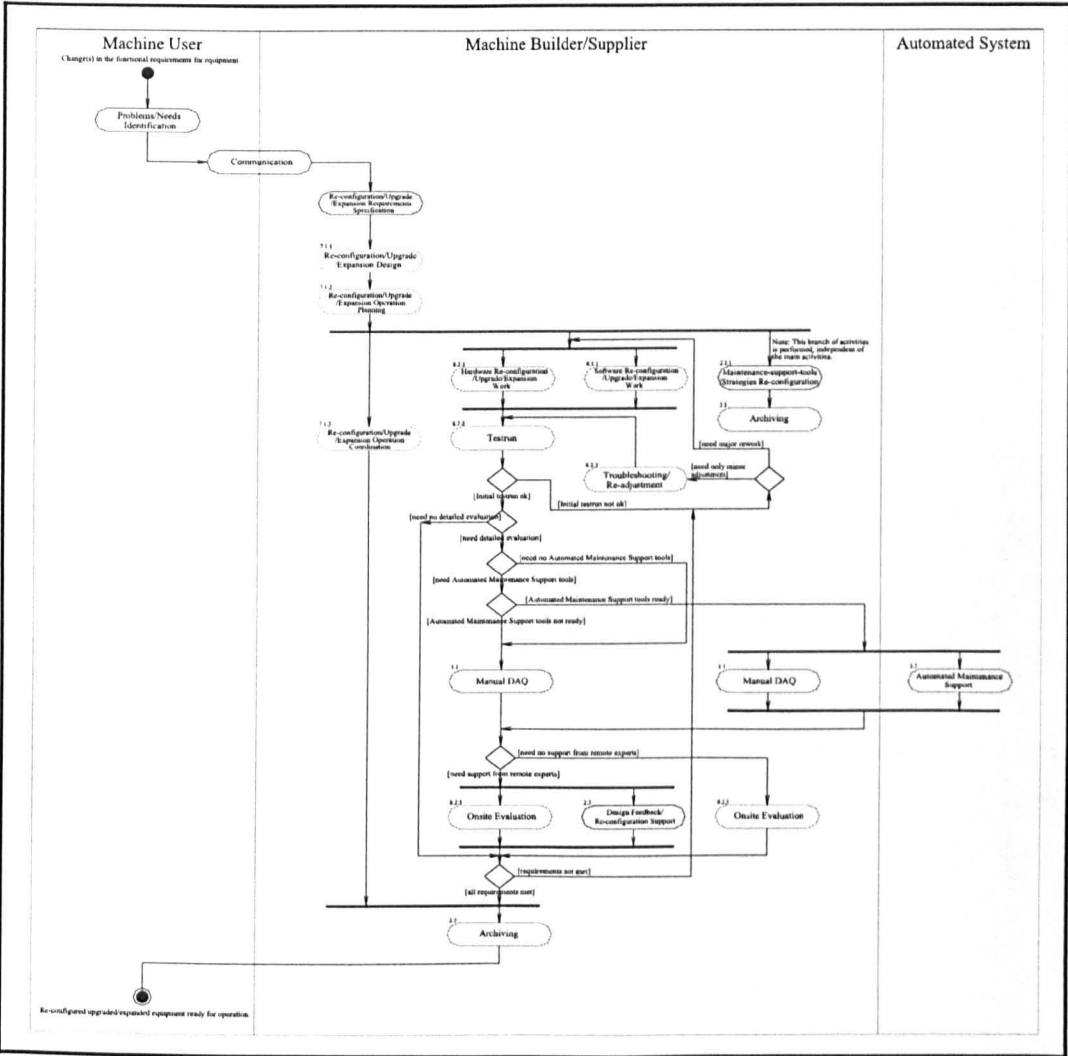
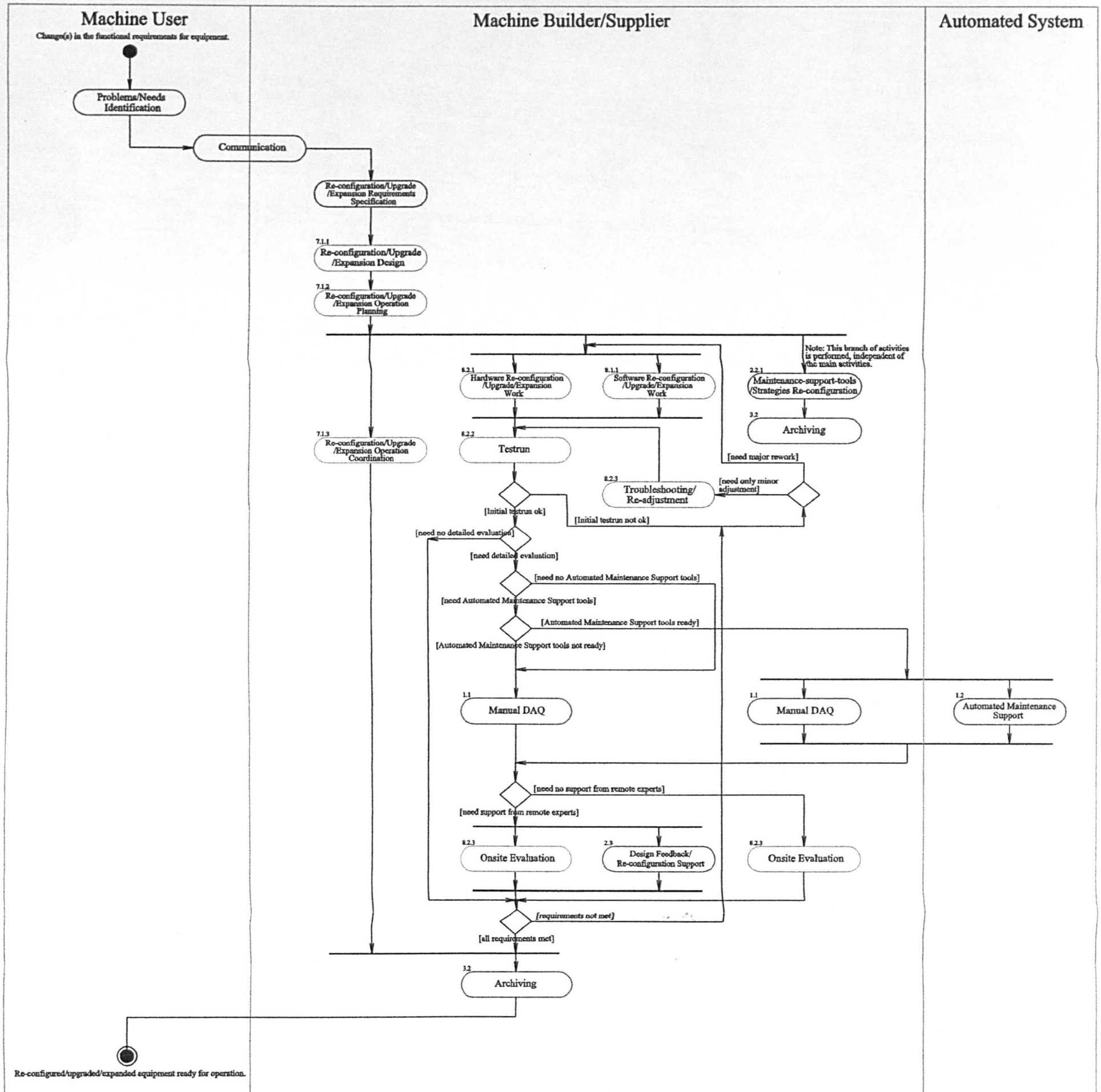


Fig. 4.5 Activity flow for scenario 5 (Please refer to the following page (A3) for an enlarged copy of this figure.)

After the completion of the planning phase, the onsite **Hardware Re-configuration/Upgrade/Expansion** work would be performed (block 8.2.1 of figure 4.4), in conjunction with the following activities (which are performed concurrently, both onsite and offsite): (1) the **Software Re-configuration/Upgrade/Expansion** work (block 8.1.1 of figure 4.4), and (2) **Maintenance-support-tool/Strategy Support** activity (block 2.2.1 of figure 4.4), which is responsible for the re-configuration of existing maintenance-support-tools/strategies. These may be followed by other necessary activities such as the



**Test-run** (block 8.2.2 of figure 4.4), **Troubleshooting/Re-adjustment** activity (block 8.2.3 of figure 4.4) and other relevant activities such as the **Onsite Evaluation** activity (block 8.2.4 of figure 4.4). The synchronisation of all the activities is provided by the **Re-configuration, Upgrade and Expansion Operation Coordination** activity (block 7.1.3 of figure 4.4). Ideally, the various activities would be completed within the planned time-scale, allowing smooth commissioning of the re-configured/upgraded/expanded equipment.

## 4.5 Chapter Summary

This chapter has presented a detailed description of a proposed advanced machine service support strategy for new generation manufacturing systems. It has presented a set of main requirements necessary for an advanced service support strategy for new generation manufacturing systems. It has also presented a detailed discussion of a process model for the proposed strategy. The proposed strategy is based on the use of a 3D-based virtual integration platform, for the integration of various onsite/offsite maintenance support (includes fault detection, diagnostics, prognostics and maintenance decision support) and extended service support (includes equipment re-configuration, upgrade and expansion support) activities. For illustrating the main ideas of the strategy advocated, five service support scenarios have been presented: (1) diagnostic/prognostic support in case of unplanned/unexpected equipment operation deviations/faults/failures, (2) periodic monitoring for condition-based preventive maintenance support, (3) maintenance-support-tool support, (4) design feedback and (5) equipment re-configuration, upgrade and expansion support. The following chapter (chapter 5) presents a detailed discussion of a 3D-based advanced service support system (i.e. the support tool), proposed for supporting the strategy presented in this chapter.

## **Chapter 5**

# **An Advanced Machine Service Support System**

### **5.1 Introduction**

This chapter presents a detailed description of a proposed 3D-based advanced machine service support system for supporting the proposed service support strategy presented in chapter 4. In this chapter, the focus is a reference architecture for the proposed service support system. First, section 5.2 presents a set of main requirements identified for the proposed system. Next, section 5.3 presents a detailed discussion of a reference architecture for the proposed system. This is followed section 5.4, which presents a description of five service support scenarios (which correspond to those presented in section 4.4 of chapter 4), illustrating how the proposed system provides support for the advanced service support strategy advocated. The last section (section 5.5) presents a summary of this chapter.

### **5.2 Requirements**

#### **5.2.1 Introduction**

The proposed service support system should provide an integrated environment where equipment data/information (design, operational and maintenance-related) and support tools could be accessed efficiently. This is required to facilitate the sharing of data/information/tools (between remote experts/engineers and site engineers/technicians), allowing the various support functions (as specified in section 4.2, chapter 4) to be performed in an integrated and efficient manner. The service support system must provide tools for the following purposes:

- (1) It must provide tools to assist remote experts (humans) in providing remote machine maintenance support for complex new generation manufacturing systems. It should provide an environment where various maintenance tools are integrated allowing the following tasks to be performed effectively and efficiently: remote machine monitoring, fault detection, diagnostics, prognostics,

maintenance action recommendation/planning, remote re-configuration of equipment (software components) and onsite maintenance services.

- (2) It must provide tools to assist remote experts (human) in developing/improving, testing and verifying existing/new maintenance-support-tools/strategies (automated/semi-automated).
- (3) It must provide tools to assist remote experts in monitoring and verifying machine performance, and identifying potential design flaws/deficiencies (or defects in an equipment system). It should also provide tools to assist in planning and performing corrective/re-configuration/improvement operations.
- (4) It must provide tools to assist machine builders/suppliers in providing extended service support (i.e. equipment re-configuration, upgrade and expansion support).

### **5.2.2 Functional Requirements**

The main requirements are:

- (1) It must provide tools for allowing remote experts to access a comprehensive set of equipment data/information (operational/maintenance-related/design-related) via low-cost communication channels, without the need for frequent site visits. Minimum sets of operational data should include the following: all data/information necessary for assessing the performance of equipment. Minimum sets of maintenance-related data/information should include the following: (1) all data/information necessary for assessing the status of equipment, identifying sources of equipment faults/failures and predicting its future trends and (2) data/information related to all historical maintenance/service activities. Minimum sets of design-related data/information should include the following: (1) all design documentation (including CAD data) and (2) original equipment manufacturers' data/information.
- (2) It should provide an integrated 3D-based virtual environment (or sets of virtual environments) where machine data/information can be managed, visualized, shared and re-used efficiently. The 3D-based virtual environment should facilitate the organization of equipment data/information into appropriate multi-view 2D/3D interactive representations, providing human users with a natural

(intuitive) environment to interact with the real equipment, locally and remotely. The support system should be capable of capturing and subsequently, allowing the 're-play' of equipment historical events in the 3D-based virtual environment (both motion and non-motion related events).

- (3) The 3D-based virtual environment should be seamlessly integrated with sets of modular automated/semi-automated maintenance-support-tools (such as data transformation, analysis, presentation (both 2D and 3D based), monitoring, diagnostic, prognostic and maintenance decision support tools). The support tools must be distributable across a local area network and the Internet in the form of appropriate tools libraries (exposed via suitable servers). Whenever appropriate, the automated maintenance-support-tools should be embedded in the equipment system. The tools libraries should be scalable where upgraded/new tools can be added easily (i.e. without requiring major re-compilation).
- (4) The 3D-based virtual environment should be seamlessly integrated with already available machine design support tools (such as mechanical and control system design support tools). The integration should facilitate the monitoring and verification of equipment performance against specifications and identification of any flaws/defects/design deficiencies.
- (5) For supporting extended service support functions, it should provide remote experts with an integrated environment allowing them to re-configure, to test and verify design changes, and to plan operations in a virtual environment before embarking on actual operations. During the execution of re-configuration/upgrade/expansion operations, it should provide an integrated environment for facilitating the coordination of onsite and offsite operations.

### **5.2.3 Non-functional Requirements**

The main requirements are:

- (1) The service support system should be based on existing facilities (both software and hardware facilities, especially they should re-use as many as possible of existing hardware facilities) without requiring major changes to be made to these facilities or without requiring special purpose facilities.

- (2) It should allow efficient re-use of already available design data/information (such as design/component specifications, test results, geometric/kinematics/dynamics models of components etc).
- (3) It must be flexible and scalable (i.e. its components must be designed to be modular and each module should not be tightly coupled with each other), allowing it to be easily re-configured (i.e. without requiring major re-compilation of software components) to accommodate changes in service support requirements during the in-service life of equipment.
- (4) It must satisfy a minimal level of equipment operational safety and security-related requirements, as follows:
  - It should not allow remote experts to have direct (remote) control of equipment. Remote experts are only permitted to acquire (i.e. to read) data/information (such as configuration and control data/information) from the control system.
  - A synchronization mechanism should be provided to facilitate coordination between the machine user's and machine builder's activities in remote re-configuration/upgrade operations. No mechanism should be provided to allow remote experts to directly effect changes in the equipment control system.
  - A fail-safe/reset mechanism to allow rapid recovery in the event of failures/errors during or after a remote re-configuration/upgrade operation must also be provided.
- (5) It must satisfy a minimal level of communication security-related requirements, as follows:
  - **Sufficient Authentication**  
An appropriate mechanism must be provided for authenticating clients' identities. All security-related data/information should be stored in a 'non-human-readable' form, in an appropriate database not accessible to the client.
  - **Data Storage and Transmission Security**  
All sensitive data/information must be stored and transmitted in encrypted form based on a proven encryption algorithm. A 'simple' encryption

algorithm may be acceptable for transmission of logger data (in order to minimize data transmission overheads). An appropriate 'data hashing' mechanism should be provided to ensure the 'originality' of data transmitted. In addition, appropriate mechanism for detecting, identifying and correcting faults due to transmission errors should also be provided.

- **Compatible with the Security Requirements of existing Facilities**

It must be compatible with the security requirements of existing facilities, i.e. its implementation/deployment should not require major adjustments to the security configurations of existing facilities.



### 5.3 Reference Architecture

#### 5.3.1 Introduction

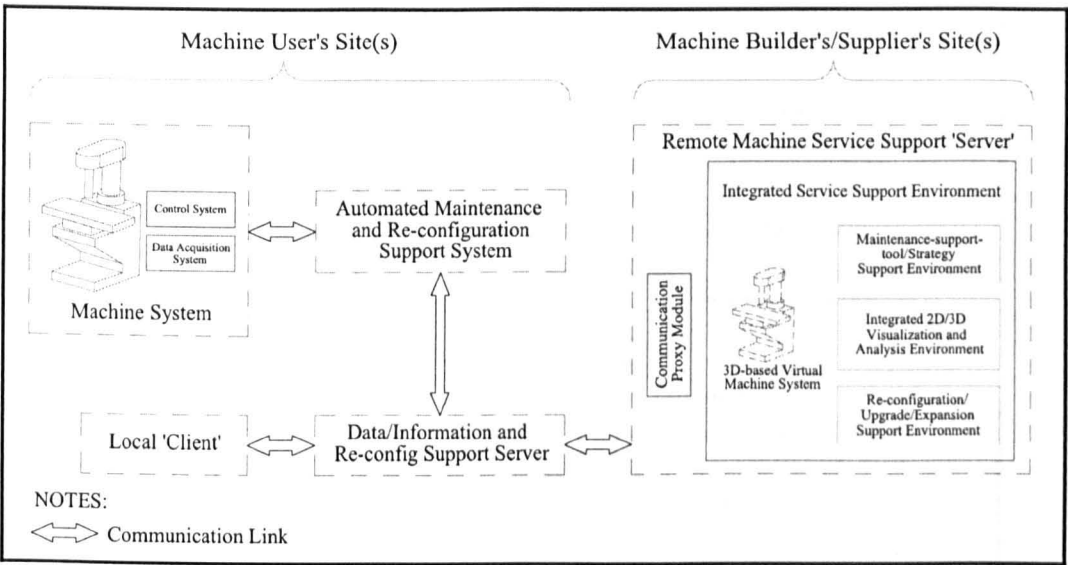


Fig. 5.1 Proposed 3D-based Advanced Machine Service Support System

The proposed 3D-based Advanced Machine Service Support System is based on the use of a 3D-based Virtual Machine System (3DVMS), as depicted in figure 5.1, to create a virtual integration platform/environment for the various service support activities, as described in section 4.3 of chapter 4. Figure 5.1 gives a simplified view of the proposed service support system (For details of each component, see figure 5.2, 5.3 and 5.4 in the following sections.). It consists of the following main components: (1) a Remote Machine Service Support 'Server' (RMS<sup>3</sup>), (2) a Data/Information and Re-configuration Support Server (DIReSS), (3) a Local 'Client' (LC), (4) an Automated Maintenance and Re-configuration Support System (AMaReSS), (5) a Machine Data Logger (MDL), (6) an array of databases and (7) sets of support tools libraries. The following sub-section (5.3.2) first presents the concept of the 3DVMS, followed by sub-section 5.3.3 to 5.3.7, which present a detailed description of each of the components of the proposed service support system.

5.3.2 Concept for a 3D-based Virtual Machine System

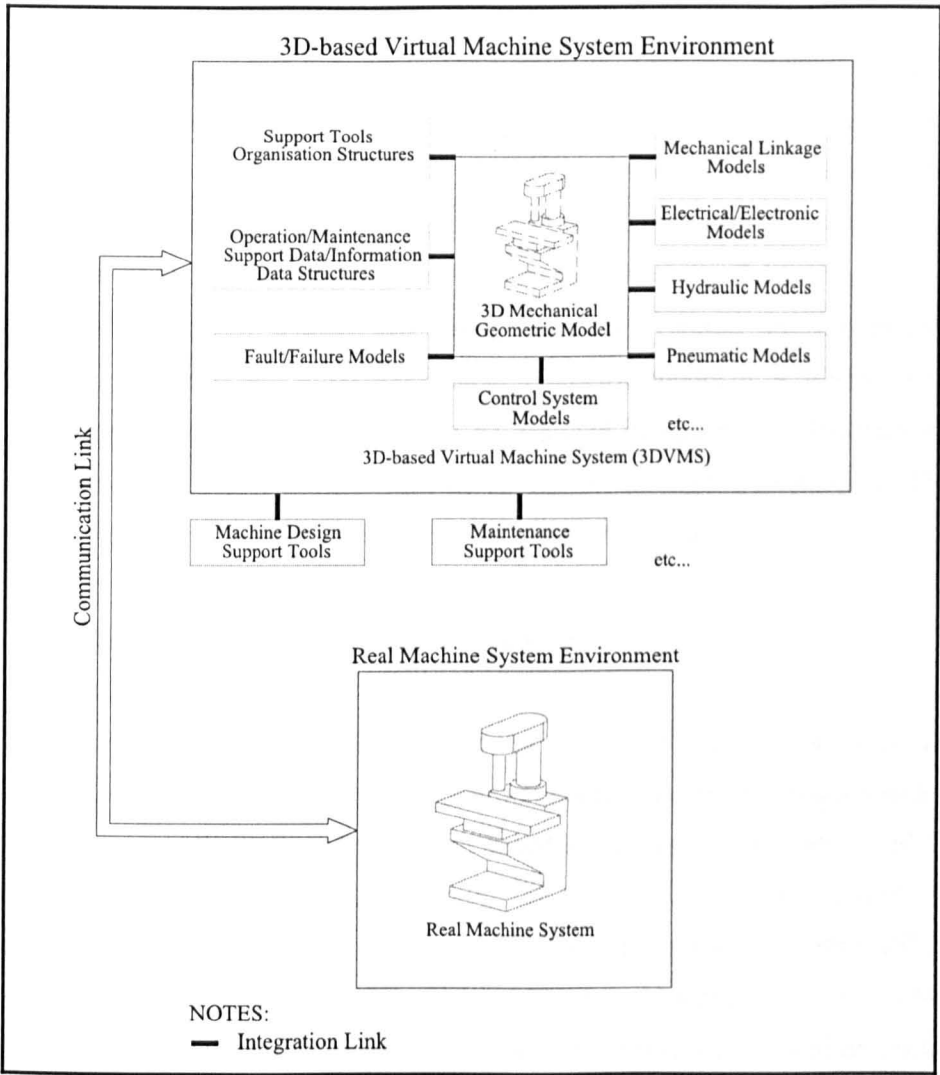


Fig. 5.2 3D-based Virtual Integration Platform

A 3D-based Virtual Machine System (3DVMS) is the virtual representation of a real machine system, which is created to provide a common reference to the real machine system. It is used as an interface to facilitate remote access to the design/operational/maintenance-related data/information of the real machine system. Due to the complexity of new generation manufacturing systems, comprehensive virtual representations are required. It must be capable of representing the various aspects of a machine system such

as mechanical geometric structures, electrical/electronic elements, hydraulic/ pneumatic elements, control system structures (both hardware and software), mechanism kinematics, dynamics behaviour, fault/failure behaviour, support tools organization structures, operational/maintenance data/information structures etc. Ideally, a 3DVMS should be based on the 3D mechanical geometric model of a machine system, created during the design and development phase. It consists of a set of 'virtual reference objects' (which is basically based on the 3D CAD entities of a 3D mechanical geometric model), which represents the various components of a real machine system. To facilitate access to different data/information sources and tools, 'links' are created between the various elements (as necessary) and a 3D mechanical geometric model in a 3D-based Virtual Machine System Environment (3DVMSE), as depicted in figure 5.2. External support tools are integrated with the 3DVMSE, as shown in the figure, creating a 3D-based Virtual Integration Platform for machine service support activities.

### **5.3.3 Remote Machine Service Support 'Server'**

#### **5.3.3.1 Introduction**

The Remote Machine Service Support 'Server' (RMS<sup>3</sup>) provides an integrated set of support tools for machine builders/suppliers to remotely access the data/information of equipment located at their clients' sites. It is based on the concept of a 3D-based Virtual Integration Platform as described in sub-section 5.3.2. The RMS<sup>3</sup> consists of the following main components: (1) an Integrated Service Support Environment (ISSE), (2) a Communication Proxy Module (CPM), (3) an array of Databases and (4) sets of Support Tools Libraries (SuToLib). The following sub-sections present a detailed description of each of the components.

#### **5.3.3.2 Integrated Service Support Environment**

The Integrated Service Support Environment (ISSE) consists of three main sub-components: (1) an Integrated 2D/3D Visualization and Analysis Environment (IVAE), (2) a Maintenance-support-tool/Strategy Support Environment (MSuTSSEn) and (3) a Re-configuration/Upgrade/Expansion Support Environment (RUESE). The following sub-sections describe each of the components in detail:

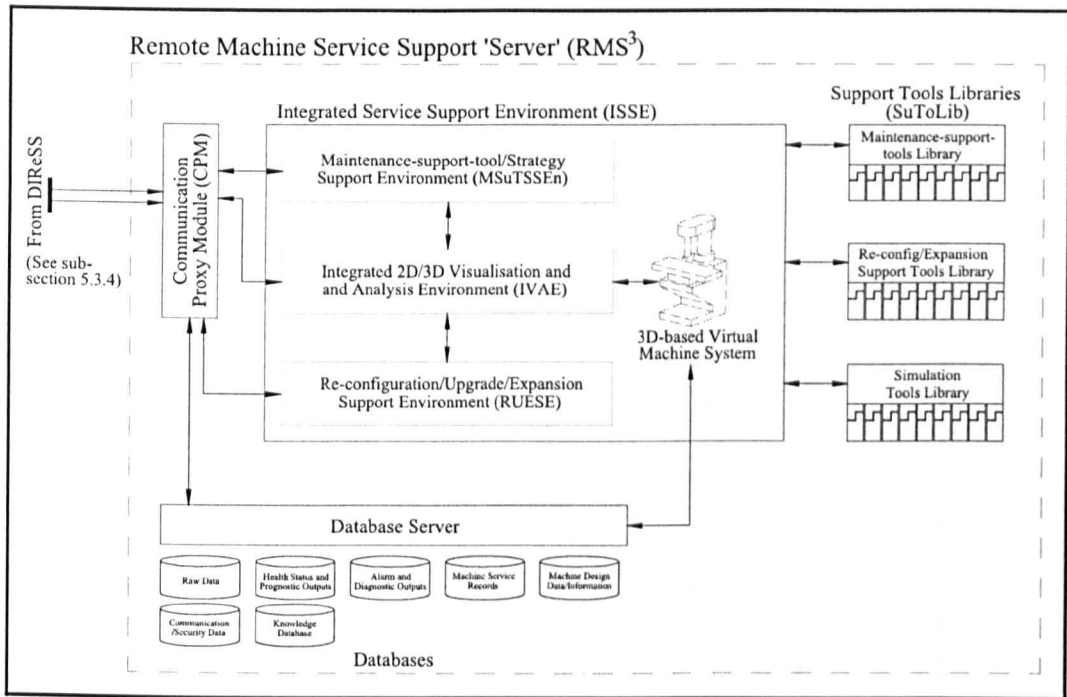


Fig. 5.3 Remote Machine Service Support 'Server'

### (1) Integrated 2D/3D Visualization and Analysis Environment

The Integrated 2D/3D Visualisation and Analysis Environment (IVAE) provides users (humans) with an integrated set of 2D and 3D-based visualization environments, serving as the main human machine interfaces (user interfaces) for interacting with a 3DVMS, as depicted in figure 5.4. With reference to the figure, the visualization environment consists of a set of interactively linked 2D and 3D-based graphic virtual environments where the different aspects of a complex mechatronics system are visualized interactively (i.e. allowing a complex system to be visualized from different 'perspectives' via interactively-linked multiple views, as shown in figure 5.4). The environment consists of the following set of visualisation environments:

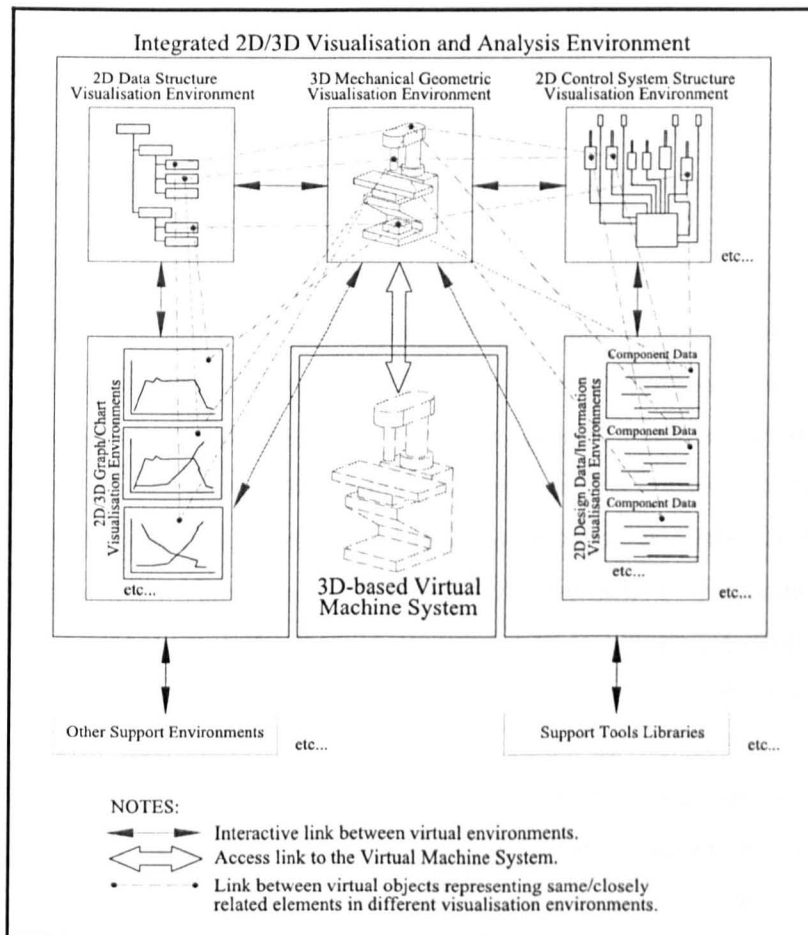


Fig. 5.4 Integrated 2D/3D Visualisation and Analysis Environment

- a) A 3D graphic visualisation environment, which provides a ‘context-sensitive’ and ‘object-sensitive’ interactive environment for the presentation and interaction with equipment mechanical geometric models. With reference to figure 5.4, it can be seen that each 3D graphic object is used as access points/links to various data/information sources and support tools associated with a corresponding real component/device (of which the 3D graphic object has been setup to represent), such as: (1) real-time/historical equipment operational data/information, (2) maintenance-support-tools (such as data/information visualization tools, transformation tools, analysis tools, diagnostic tools, prognostic tools etc), (3) access points/links for interacting

with other visualisation environments, (4) setup tools (such as those for: setting up connections with equipment data sources, the kinematics structure of virtual equipment, support tools libraries etc), (5) additional graphic setup tools for setting up/manipulating the attributes of the graphic entities in the virtual environment.

- b) Additional graphic/textual virtual environments (either 2D or 3D-based) for the visualization of other aspects of a machine system (such as electrical/electronic connection, control system (both hardware and software), mechanism kinematics, data structures, support tools organization, design/operational/maintenance-related data/information). These additional virtual environments are 'inter-linked' and 'coordinated' with the main 3D virtual environment, providing a set of highly interactive environments for the simultaneous visualization of complex sets of equipment data/information. Each of the virtual environments may also include a set of support tools similar to those described in (a) above.
- c) A set of 2D/3D-based animation/simulation (graphic simulation) support modules for supporting the animation-based visualization of equipment operations/events (both real and simulated operations). The modules allow synchronized animation to be performed simultaneously in various graphic virtual environments, based on input data from pre-set data sources, which could either be real-time or non-real-time, real-life or simulated.
- d) A set of communication support modules responsible for supporting communication with other modules such as the Communication Proxy Module (CPM, see sub-section 5.3.3.3 for details.), databases (See sub-section 5.3.3.4), Support Tools Libraries (SuToLib, see sub-section 5.3.3.5.).

## **(2) Maintenance-support-tool/Strategy Support Environment**

The main purpose of the Maintenance-support-tool/Strategy Support Environment (MSuTSSEn) is to provide an integrated environment for supporting the operations of automated maintenance-support-tools (See the AMaReSS described in sub-section 5.3.6 for further details.). It is tightly integrated with the

Integrated 2D/3D Visualization and Analysis Environment (IVAE) (as depicted in figure 5.3), allowing equipment operational data/information to be accessed intuitively and efficiently (from within the MSuTSSEn). It consists of a set of the following tools:

- a) A visualization and analysis environment for analysing and verifying the performance of installed automated maintenance-support-tools. Additional support tools are provided via external library ‘plug-ins’/interfaces.
- b) An authoring environment, where upgraded/new automated maintenance-support-tools/strategies are developed, analysed, debugged, tested, verified (based on either real operational data or simulation outputs, or both). Verified/obsolete algorithms/tools may then be remotely installed into or removed from the Automated Maintenance and Re-configuration Support System (See the AMaReSS in sub-section 5.3.6 for further details.).

**(3) Design Feedback, Re-configuration, Upgrade and Expansion Support Environment**

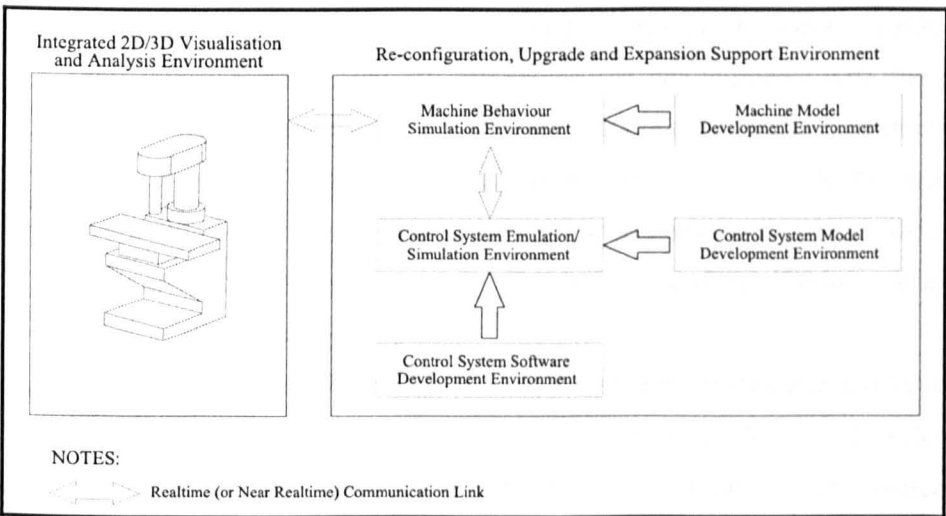


Fig. 5.5 Re-configuration, Upgrade and Expansion Support Environment

The main function of the Design Feedback, Re-configuration, Upgrade and Expansion Support Environment (DeFRUESE) is to provide a set of tools to

support equipment design verification, re-configuration, upgrade and expansion operations. Similar to the MSuTSSEn, it is tightly integrated with the Integrated 2D/3D Visualisation and Analysis Environment (IVAE) (as depicted in figure 5.5), allowing equipment operational data/information to be accessed efficiently (from within the DeFRUESE). It provides a set of the following tools:

- a) A design support environment, which provides a set of visualization and analysis tools for the purpose of verifying equipment performance against design specifications (this environment is embedded in the IVAE). It assists users (humans) in capturing real life experience and knowledge about the operations of equipment. Accumulated experience and knowledge can then be used as the basis for: (1) design flaw identification and correction/removal, (2) performance optimization, (3) equipment re-configuration/upgrade/expansion support and (4) future design improvement.
- b) A set of virtual support environments for mechanical/electro-mechanical systems upgrade/re-configuration/verification support (depicted as the Machine Model Development Environment and the Machine Behaviour Simulation Environment in figure 5.5). These virtual environments provide users with tools to 'virtually' upgrade/re-configure the mechanical/electro-mechanical components. By integrating the environments with the IVAE (where the virtual mechanical components may be manipulated interactively), experiments/tests and verification of new configurations could be performed 'virtually' before embarking on actual operations. Additional simulation tools are provided via appropriate 'plug-ins' or interfaces (for integration with external tools/applications).
- c) A set of virtual environments for control systems upgrade/re-configuration/verification (depicted as the Control System Model Development Environment, the Control System Software Development Environment and the Control System Emulation/Simulation Environment in figure 5.5.). These environments provide users with tools to virtually upgrade/re-configure the control system hardware/software. It provides an authoring environment where control system software can be developed, tested, debugged and



verified in conjunction with the environments described in (a) and (b) above. Additional support tools (e.g. in the form of additional simulation models and emulation tools) may be integrated with the environment via external library 'plug-ins'/interfaces. It also provides tools to facilitate remote installation of upgraded/new control system software modules/components into the real equipment control system (See the AMaReSS in sub-section 5.3.6 for further details.).

### **5.3.3.3 Communication Proxy Module**

The Communication Proxy Module (CPM) manages all details and procedures for communication with the Data/Information and Re-configuration Support Server (See the DIReSS in sub-section 5.3.4 for further details.), on behalf of the Integrated Service Support Environment (ISSE, a component of the Remote Machine Service Support Server (RMS<sup>3</sup>)). It can be configured at run-time for using different communication protocols, target servers and communication modes. It allows the ISSE to communicate with different DIReSSs based on available network facilities (depending on whether a DIReSS is located on a public/private network or local/wide area network). Its main functions are: (1) managing the communication of data/information between the ISSE and the DIReSS, (2) managing communication-related data/information (such as user accounts, access log, errors etc), (3) performing security-related functions (users' authentication, data encryption/decryption, data validity checks etc) and (4) communication error management (such as user notification and error recovery).

### **5.3.3.4 Databases**

These are the machine builder's/supplier's local databases, which store only a subset of data/information downloaded from the equipment Data/Information and Re-configuration Support Server (DIReSS). It consists of a group of databases with the same/similar structure as the main databases in the DIReSS. The main difference between the two sets of databases (apart from quantity of data stored) lies in the Machine Design Data/Information Database (MaDDID). Typically, the machine builders'/supplier's copy of MaDDID stores a more comprehensive set of equipment design and

development data/information, which may consist of all relevant data sheets/specifications (such as component data sheets and technical specifications etc), CAD data (2D or 3D), models (such as kinematics models, dynamics models etc) etc. See sub-section 5.3.4.4 for further details about other databases.

### **5.3.3.5 Support Tools Libraries**

The Support Tools Libraries (SuToLib) consist of a set of scalable and re-configurable tools libraries in the form of 'plug-ins' and interfaces, to facilitate the integration of the ISSE with external applications/tools. The sets of libraries may consist of one or more of the following:

#### **(1) Maintenance-support-tools Library**

This library provides a set of tools 'plug-ins'/interfaces for accessing tools required to support maintenance support tasks such as data presentation/visualization, transformation, analysis, diagnostic, prognostic and decision support tools.

#### **(2) Design support, Re-configuration, Upgrade and Expansion Support Tools Library**

This library provides a set of tools 'plug-ins'/interfaces for accessing tools required for equipment design verification, re-configuration, upgrade and support such as design/re-configuration visualization, analysis and decision support tools.

#### **(3) Simulation Tools Library**

This library provides a set of tools 'plug-ins'/interfaces for accessing model construction/manipulation tools, simulation tools and models.

## **5.3.4 Data/Information and Re-configuration Support Server**

### **5.3.4.1 Introduction**

The Data/Information and Re-configuration Support Server (DIRESS) is the main data/information server, which provides a uniform equipment data/information access interface for external systems over the network/Internet. It also provides an interface for communicating with the Automated Maintenance and Re-configuration support System (See AMaReSS in sub-section 5.3.6.). It consists of the following three main sub-

components: (1) a Communication Server, (2) a Logging Module and (3) an array of databases.

#### **5.3.4.2 Communication Module**

The Communication Module (CM) provides the main program interface for external systems to access data/information in central databases over the network/Internet. It supports multiple communication protocols, allowing it to communicate with different data clients. Types of protocols used depend on where a data client is located on a network (i.e. either on a public/private or local area/wide area network). Its main functions are: (1) managing the communication of data/information between the ISSE (a component of the RMS<sup>3</sup>) via the CPM and the rest of the DReSS's components or with the Automated Maintenance and Re-configuration Support System (AMaReSS, see sub-section 5.3.6 for further details.), (2) managing communication-related data/information (such as user accounts, access log, errors etc), (3) performing security-related functions (users' authentication, data encryption/decryption, data validity checks etc) and (4) communication error management (such as user notification and error recovery).

#### **5.3.4.3 Logging Module**

The Logging Module (LM) is the main module, which manages all equipment data/information-logging operations. It synchronizes and performs logging operations of the outputs of the Automated Maintenance and Re-configuration Support System (AMaReSS) (such as what data to log, log sequences and where to store the data etc). Depending on the outputs of the AMaReSS and user settings, logging may be initiated and performed periodically (i.e. at regular intervals) or 'on-demand' (i.e. initiated/activated by users, such as when a situation arises). It may be triggered manually or automatically, locally or remotely. In the automatic trigger mode, logging operations are initiated via a set of pre-programmed schedules (pre-set dates, times and event types) or by the outputs of AMaReSS modules (such as additional logging operations may be initiated when the outputs of an AMaReSS module indicates that more data from an equipment system is required for further analysis by users (humans) etc).

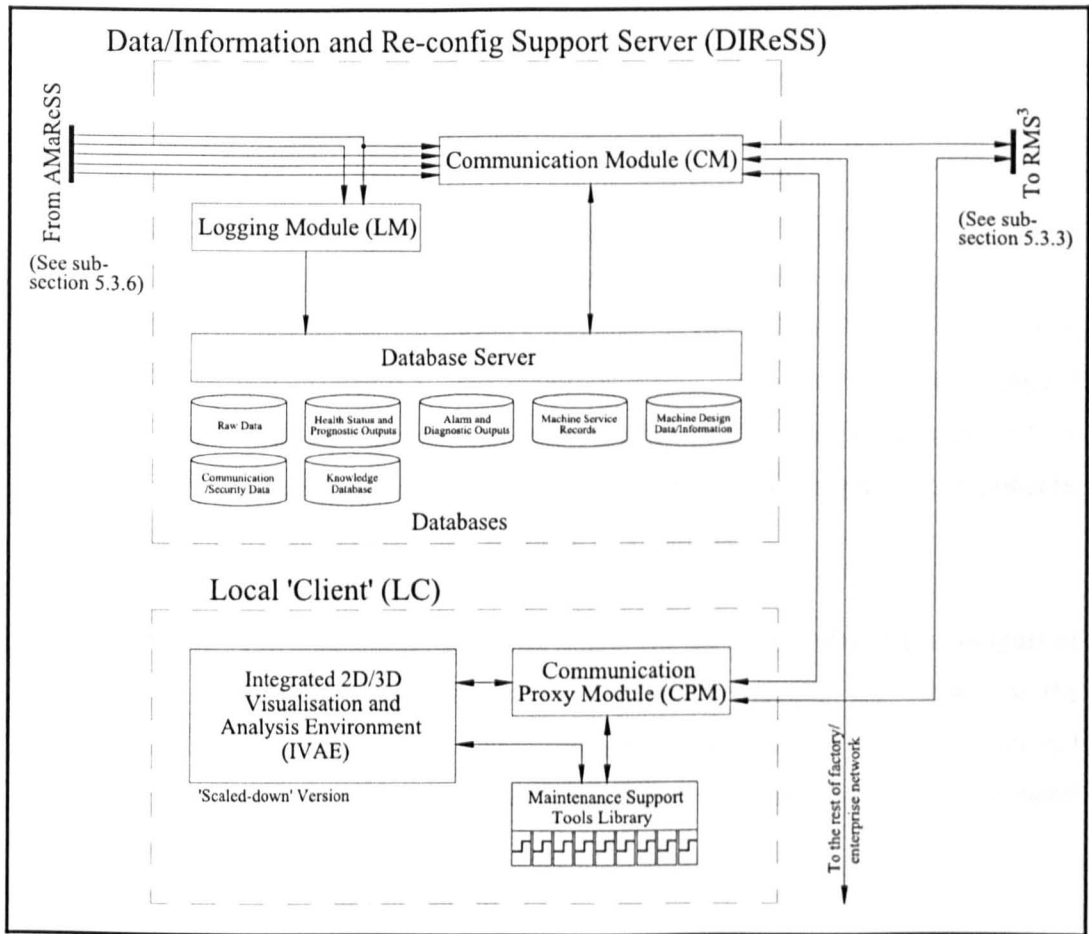


Fig. 5.6 Data/Information and Re-configuration Support Server and Local 'Client'

#### 5.3.4.4 Databases

These are the central databases, storing a comprehensive set of equipment operational data/information. They are accessible over the network/Internet via the Communication Module (CM). They consist of the following sets of databases:

(1) Raw Data Database

A Raw Data Database (RDD) stores raw operational data mainly in the form of time-series digitized data. It may also store data in other 'pre-processed' forms such as in the form of frequency-series data etc. Additional accompanying data/information is also logged for log session management. The additional data/information consists of: (1) a set of log session information (such as the date, log time, log interval, log reference number etc), (2) a set of equipment reference

information (such as machine system/component identification numbers etc), (3) a set of log parameter information (such as parameter names, units, categories etc) and (4) 'event link' reference (such as reference to alarm events, diagnostics and prognostics sessions, equipment failure/stoppage events etc).

**(2) Health Status and Prognostics Database**

A Health Status and Prognostics Database (HeSProD) stores the outputs of the Health Assessment and Prognostics Modules of the AMaReSS (See sub-section 5.3.6.6 for further details.). The historical health status data/information logged over a period of time is used as input for the Prognostics Module(s) to predict the future trends and the remaining useful lives (RUL) of equipment components. The prognostic outputs are then stored in this database.

**(3) Alarms and Diagnostics Database**

An Alarms and Diagnostics Database (ADD) stores mainly alarms (the outputs of the automated Monitoring Modules) and diagnostic results (the outputs of the automated Diagnostic Modules). The database may also store additional reference data/information such as alarm-trigger thresholds for each component/device.

**(4) Machine Service Records Database**

A Machine Service Records Database (MaSReD) stores all the historical service records of equipment. The records consists of machine supplier maintenance/upgrade recommendations/instructions, service work orders, spare part orders, service work records, upgrade records, maintenance work evaluation records etc.

**(5) Machine Design Data/Information Database**

A Machine Design Data/Information Database (MaDDID) stores a sub-set of equipment design and development data/information, which may consist of relevant data sheets/specifications (such as component data sheets and technical specifications etc), CAD data (2D or 3D), models (such as kinematics models, dynamic models etc) etc. A comprehensive set of such data/information is stored in the machine builder's/supplier's database (as described in sub-section 5.3.3.4).

**(6) Communication/Security Data Database**

A Communication/Security Data Database (CoSDaD) stores all communication and security-related data/information. It may consist of data/information about the client (such as its identification and privilege level etc), Communication Module (CM, a component of the DIReSS, see sub-section 5.3.4.2 for details.) (such as the server URL, communication protocols etc), Communication Proxy Module (CPM) (such as its name and socket port), security-related data (such as access usernames, passwords and security keys) etc.

(7) Knowledge Database

A knowledge Database (KD) stores a comprehensive set of previous 'cases' or 'knowledge' of equipment faults and the corresponding recommended/successful remedial actions, used mainly by automated Diagnostics, Prognostics Modules (for automated/semi-automated reasoning/root cause inference) and for user reference.

### **5.3.5 Local ‘Client’**

#### **5.3.5.1 Introduction**

The Local ‘Client’ (LC) provides the main human-machine-interface (HMI) for machine site engineers/operators to access data/information stored in the Data/Information and Re-configuration Support Server (DIReSS). It consists of: (1) a ‘scaled-down’ version of the Integrated 2D/3D Visualization and Analysis Environment (See the IVAE as described in sub-section 5.3.3.), (2) a Communication Proxy Module (CPM) (Similar to that described in sub-section 5.3.3.) and (3) a Maintenance-support-tools Library (Similar to that described in sub-section 5.3.3.).

#### **5.3.5.2 Integrated 2D/3D Visualization and Analysis Environment (Client Version)**

This is a ‘scaled-down’ version of the Integrated Visualization and Analysis Environment (IVAE), which may be used as or integrated with a local Supervisor Control and Data Acquisition system (SCADA). It provides the main user interface for machine site engineers/operators to access data/information and a set of support tools, required for the local support of equipment. It comprises a sub-set of the tools/modules (of the main IVAE as described in sub-section 5.3.3) tailored to the specific needs of a particular machine user. It also provides an interface for onsite technicians/engineers to communicate with remote machine experts/engineers.

### **5.3.6 Automated Maintenance and Re-configuration Support System**

#### **5.3.6.1 Introduction**

The Automated Maintenance and Re-configuration Support System (AMaReSS) consists of a set of highly integrated and modular automated service support tools/modules, as shown in figure 5.7, providing: (1) continuous maintenance support (such as monitoring, health assessment, diagnostics, prognostics, etc) for equipment, (2) re-configuration support for automated maintenance-support-tools and (3) re-configuration support for the equipment control system. Figure 5.8 shows a hierarchical organisation of the components/modules of the AMaReSS.

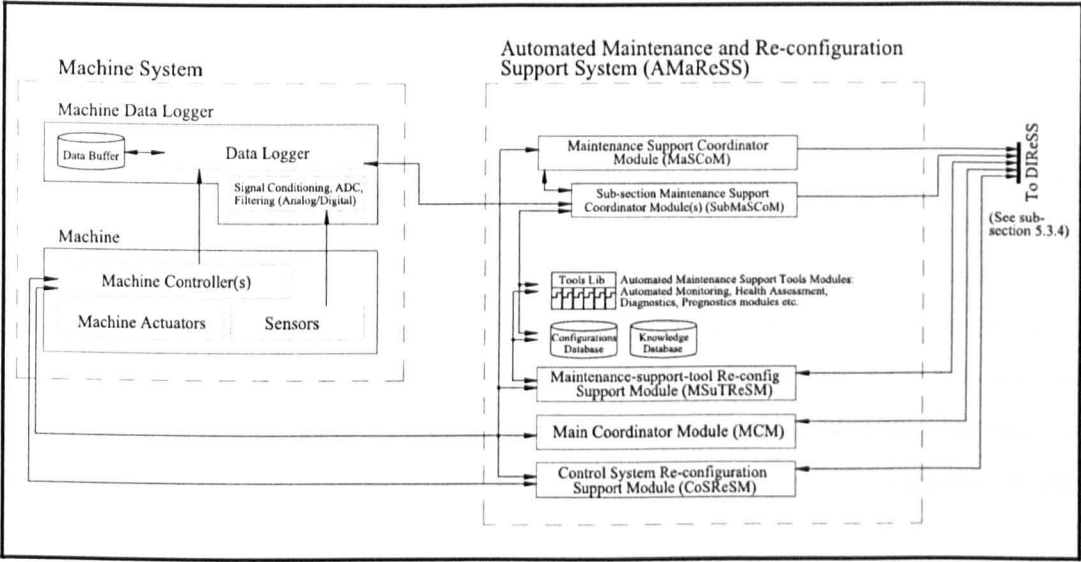


Fig. 5.7 Automated Maintenance and Re-configuration Support System

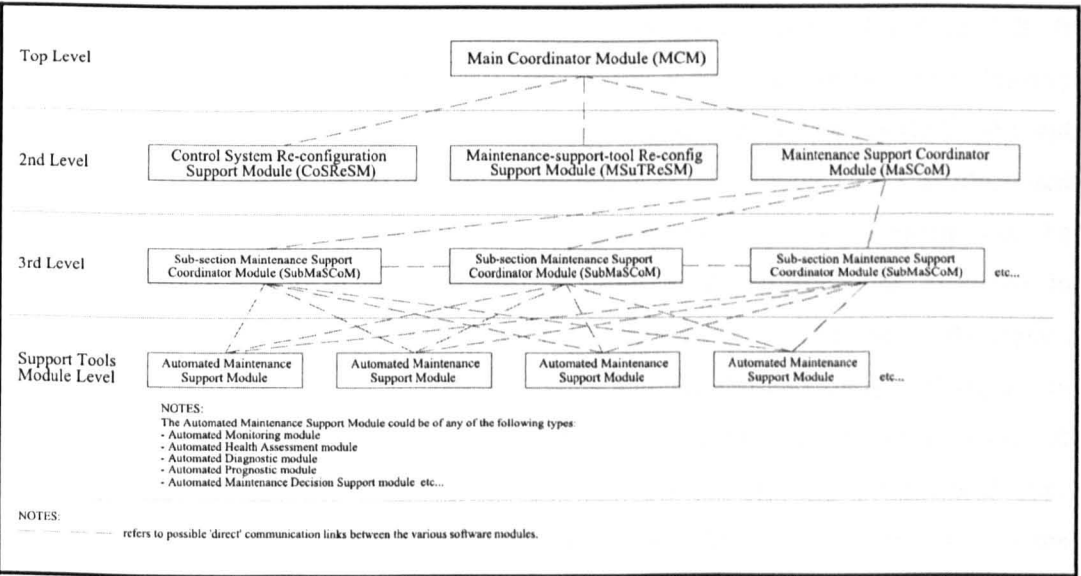


Fig. 5.8 Hierarchical organisation of the AMaReSS's components

As depicted in figure 5.8, it consists of the following four main groups of modules: (1) a top level Main Coordinator Module (MCM, details are presented in sub-section 5.3.6.2), which is responsible for the direct coordination of all the second level



modules of the AMaReSS (See (2), (3) and (4) that follow.), (2) a Maintenance-support-tool Re-configuration Support Module (MSuTReSM, details are presented in sub-section 5.3.6.3), which is responsible for the remote re-configuration support of equipment maintenance-support-tools, (3) a Control System Re-configuration Support Module (CoSReSuM, details are presented in sub-section 5.3.6.4), which is responsible for the remote re-configuration support of equipment control system software, and (4) a Maintenance Support Coordinator Module (MaSCoM, details are presented in sub-section 5.3.6.5), which is responsible for the coordination of the third level Sub-section Maintenance Support Coordinator Modules (SubMaSCoM, details are presented in sub-section 5.3.6.6.). The following sections present more detailed descriptions of the modules.

#### **5.3.6.2 Main Coordinator Module**

The Main Coordinator Module (MCM) acts as the main coordinator of the operations of all the lower level modules of the AMaReSS, as illustrated in figure 5.8. It is also responsible for maintaining the synchronization of the operations of the AMaReSS with those of the Data/Information and Re-configuration Support Server (DIRESS) and the Machine Data Logger (MDL, details are presented in sub-section 5.3.7.), as illustrated in figure 5.7. It directly coordinates the operations of the second level modules of the AMaReSS, which consist of the MSuTReSM, CoSReSuM and MaSCoM, as shown in figure 5.8. Figure 5.9 shows the operation flow of the MCM. As depicted in the figure, the operations start with the MCM communicating with the DIRESS for identifying a pre-set/requested operation mode. Once the relevant data/information for a requested operation is received (from the DIRESS) and confirmed, the MCM will start synchronizing with other sub-systems/modules of the AMaReSS. Depending on the priority level of a request and the current operations of equipment, the MCM will, either defer the request until the completion of current operations or interrupt immediately. Once it is ready, it initiates and delegates the request to an appropriate second level module of the AMaReSS, which is responsible for the actual execution of the requested operation. All data/information relevant to the last states of interrupted operations are stored by the MCM before the start of the requested operation. The data/information will

then be retrieved at a later stage for the resumption of interrupted operations once the interrupting operation is completed. During various operations in different modes, communication with the DIReSS is maintained by the MCM. Such communication is required to ensure that the operations of the various components/modules of the AMaReSS are synchronized with each other and with those of the DIReSS and MDL. After the completion of the requested operation, outcomes of the operation are reported to the MCM, which will then decide on further actions.

There are four modes of operations for the AMaReSS, which are under the direct coordination of the MCM, there are:

(1) Automated Maintenance Support Mode

In this mode, the AMaReSS is operating autonomously, reporting to users (humans), automatically (as necessary) the outcomes of maintenance support operations. This mode of operation is represented as the 'Mode 1' operation in figure 5.9. In this case, the MCM initiates and delegates maintenance support operations to the Maintenance Support Coordinator Module (See the MaSCoM in sub-section 5.3.6.5 for further details.). During an autonomous support process, the MCM is in constant communication with the MaSCoM. It continuously evaluates feedback from the MaSCoM, making decision on further actions and to coordinate with the DIReSS and MDL. An autonomous support operation continues until an interruption signal is received from the MCM (for example, when requests for other operations are received from other sub-system components/modules etc).

(2) Partially-automated Maintenance Support Mode

In this mode, maintenance support operations are initiated and managed by users (i.e. manually, not via a pre-set schedule/trigger event and users are in control of the operation sequences), with or without the support of automated maintenance-support-tools. This mode of operation is represented as the 'Mode 2' operation in figure 5.9. Similar to the first case above, the MCM initiates and delegates maintenance support operations to the MaSCoM. However, being different from the first case (the Automated Maintenance Support Mode), the MCM only

initiates user requested operations, which may involve only a sub-set of SubMaSCoMs. Once requested operations are completed, outcomes are reported to users. No further operation is performed until a new request is received from users.

**(3) Maintenance-support-tool Re-configuration/Upgrade Mode**

In this mode, the MCM initiates and delegates support operations to the Maintenance-support-tool Re-configuration Support Module (MSuTReSM). This mode of operation is represented as the 'Mode 3' operation in figure 5.9. In this case, the support operation is typically initiated by the machine builder/ supplier when new automated maintenance support module upgrades/bug fixes/ new modules/components are available. Depending on the user pre-set priority level, re-configuration operations may be performed immediately, interrupting all or parts of in-progress support operations or postponed until after all or parts of in-progress operations are completed (See the MSuTReSM in sub-section 5.3.6.3 below for further details.).

**(4) Control System Software Re-configuration/Upgrade Mode**

In this mode, the MCM initiates and delegates the support operations to the Control System Re-configuration Support Module (CoSReSM). This mode of operation is represented as the 'Mode 4' operation in figure 5.9. Support operations are typically initiated by the machine builder/supplier when new control system software upgrades/bug fixes/new modules/components are available. For these operations to be performed efficiently, synchronization with equipment operations is required (See the CoSReSM in sub-section 5.3.6.3 below for further details.). Once permission for the re-configuration operation is granted by onsite engineers/technicians, the CoSReSM will perform the necessary installation/re-configuration operations. Verification of the newly installed components will then be performed in collaboration with onsite engineers/ technicians.

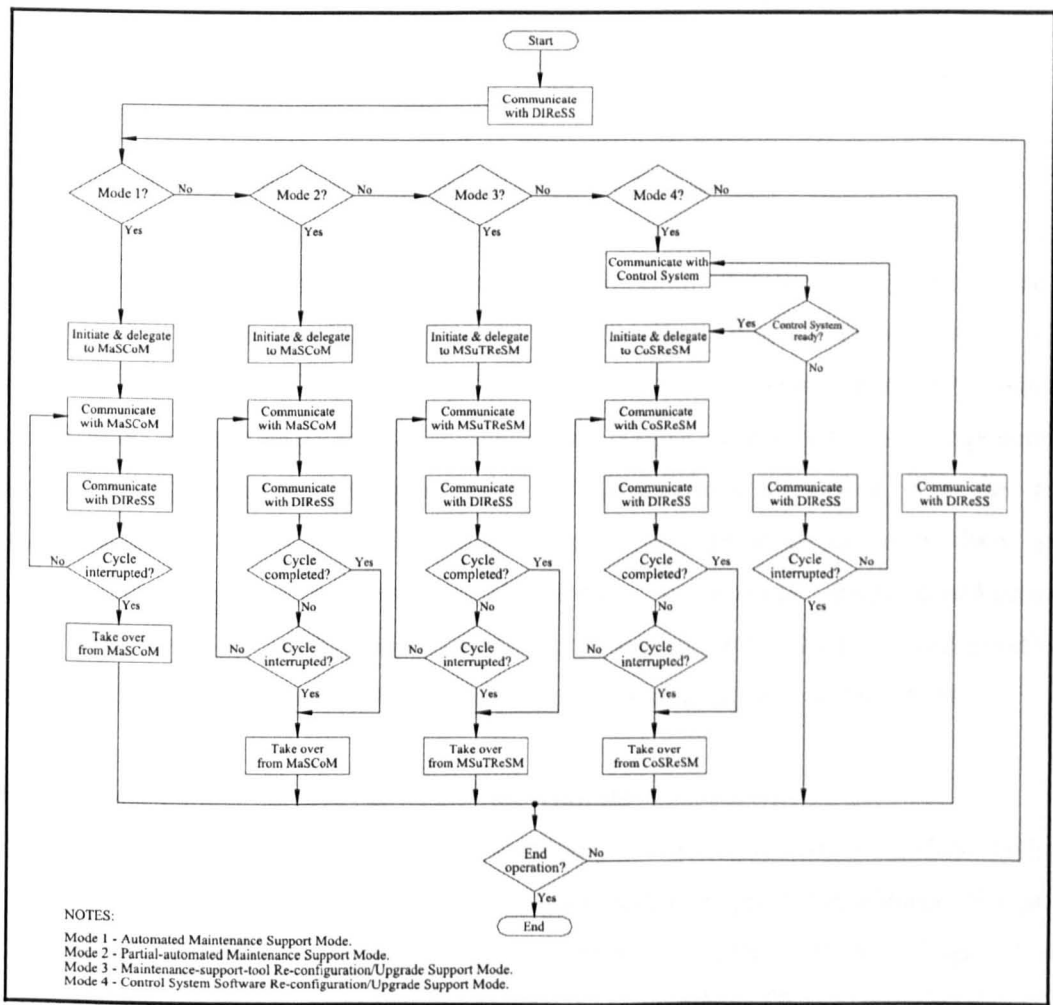


Fig. 5.9 Main Coordinator Module operation flow

### 5.3.6.3 Maintenance-support-tool Re-configuration Support Module

The main function of the Maintenance-support-tool Re-configuration Support Module (MSuTReSM) is to assist in the remote re-configuration of automated maintenance support modules. It is responsible for coordinating the following re-configuration processes: (1) the installation of one or more automated support module upgrades, (2) the installation of one or more new automated support modules, (3) the re-configuration of all or parts of a maintenance-support-tool organizational structure, for example when there are changes in equipment configurations/functions. It receives direct

coordination commands from the MCM, performs one or more re-configuration operations and reports the status/outcomes of the operations directly to the MCM.

#### **5.3.6.4 Control System Re-configuration Support Module**

The main function of the Control System Re-configuration Support Module (CoSReSuM) is to assist in the remote re-configuration of equipment control system software. It is responsible for coordinating the following re-configuration processes: (1) the re-configuration of control system parameters, for equipment performance optimization, (2) the re-configuration/upgrade of control system software components, for equipment performance optimization or faults/errors correction, (3) the re-configuration of control system software components, for example when there are changes in equipment configurations/functions. It receives direct coordination commands from the MCM, performs one or more control system re-configuration operations and reports the status/outcomes of the operations directly to the MCM.

#### **5.3.6.5 Maintenance Support Coordinator Module**

The main function of the Maintenance Support Coordinator Module (MaSCoM) is to coordinate the operations of Sub-section Maintenance Support Coordinator Modules (See the SubMaSCoM in sub-section 5.3.6.6 below for further details.). Figure 5.10 shows the operation flow of the MaSCoM. Similar to the MSuTReSM and CoSReSuM, it receives direct coordination commands from the MCM. It is responsible for coordinating the following operations: (1) routine reporting of the outputs of automated maintenance support activities for coordinated decision-making and support actions, (2) coordination of automated maintenance support activities with other support activities when intervention requests are received from users for additional logging operations, not pre-programmed in the automated procedures, (3) coordination of automated maintenance support activities with the activities of the MSuTReM when automated maintenance-support-tool re-configuration/upgrade requests are received from the MCM and (4) coordination of automated maintenance support activities with the activities of the CoSReSuM when control system re-configuration/upgrade request(s) are received from the MCM. With reference to figure 5.8, the MaSCoM is a second level coordinator

module, which is responsible for the direct coordination of all maintenance support activities. In order to facilitate the coordination of maintenance support operations for a complex system, the support operations are split into smaller sub-sets of operations. This hierarchical organisation of the system is illustrated in figure 5.8. Each sub-set is responsible for providing maintenance support for a sub-section of a complex system.

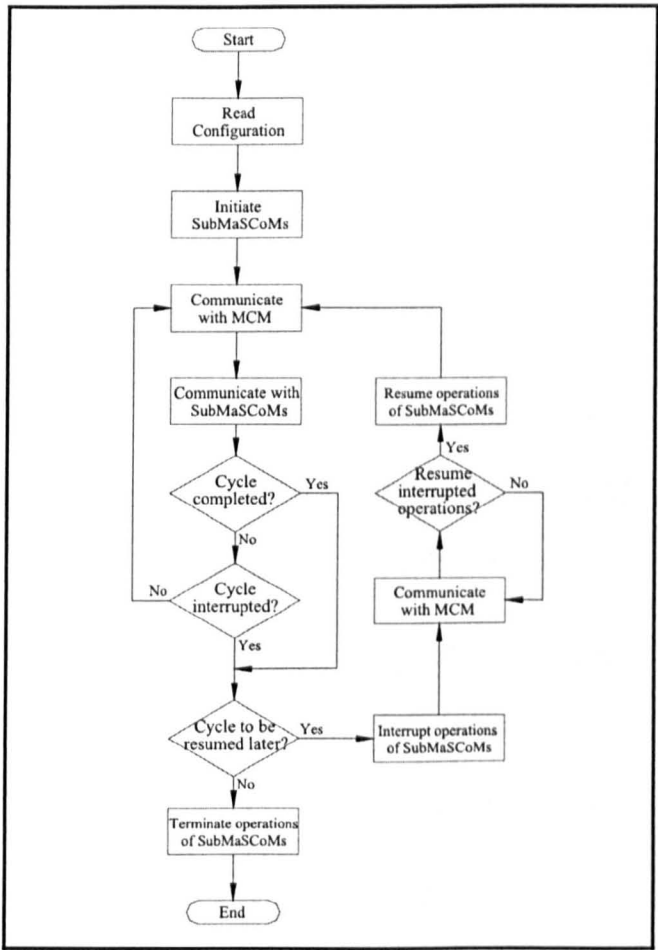


Fig. 5.10 Maintenance Support Coordinator Module operation flow

The term ‘sub-section’ in this case refers to one or a group of inter-related components (mainly from the perspective of maintenance support), such as an actuator or a group of actuators. The responsibility of coordinating each sub-set of operations is delegated to a SubMaSCoM. As shown in figure 5.10, the MaSCoM maintains communication with

both the MCM and SubMaSCoMs during automated support operations. It continuously reports the outputs of maintenance support modules to the MCM. Depending on commands from the MCM, the MaSCoM may interrupt/terminate the operations of all or parts of SubMaSCoMs.

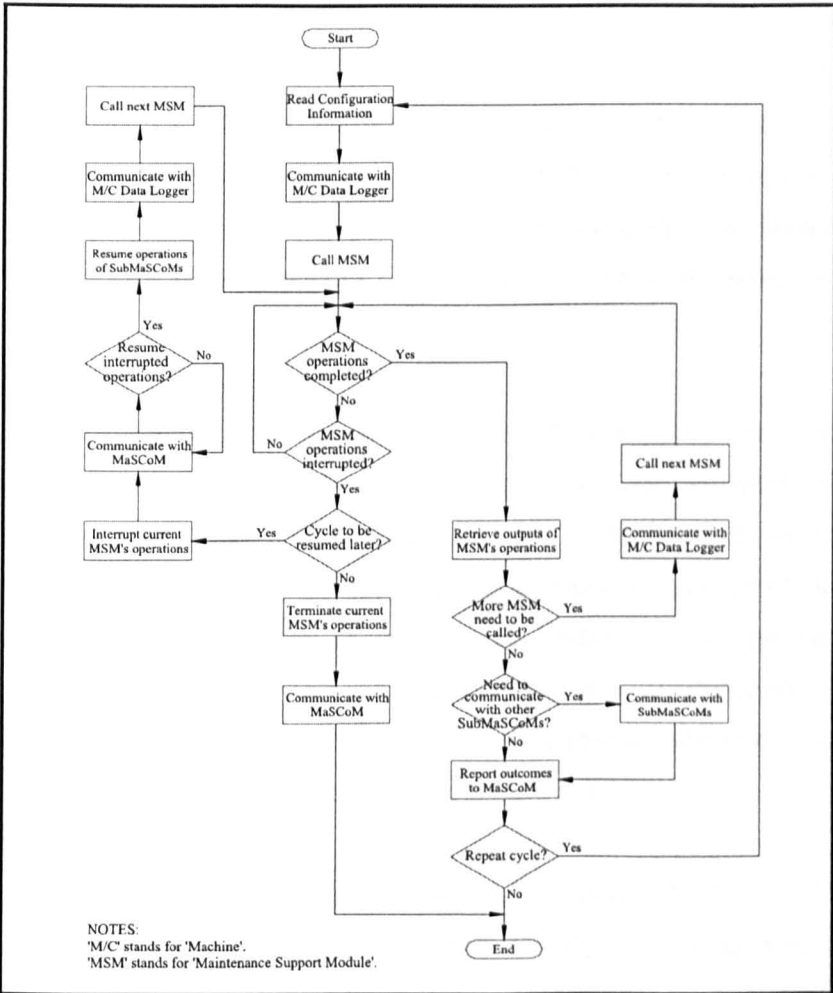


Fig. 5.11 Sub-section Maintenance Support Coordinator Module operation flow

5.3.6.6 Sub-section Maintenance Support Coordinator Modules

The main function of a Sub-section Maintenance Support Coordinator Module (SubMaSCoM) is to coordinate automated sub-section level maintenance support activities. With reference to figure 5.8, a SubMaSCoM is on the third level of the

organization of the AMaReSS. In general, each SubMaSCoM may communicate with a set of automated maintenance support modules assigned with the task of processing data associated with the operations of components within a sub-section. Figure 5.11 shows the operation flow of a SubMaSCoM. A SubMaSCoM coordinates directly the operations of the different sets of automated maintenance support modules. When necessary, SubMaSCoMs may communicate with each other for sharing data/information. They receive direct coordination commands from the Maintenance Support Coordinator Module (MaSCoM), perform one or more routine maintenance support operations and report the status/outcomes of the operations directly to the MaSCoM. Depending on the configurations, one or more maintenance support modules may be called. The following sections present descriptions of some of the main categories of maintenance support modules:

(1) Monitoring Module

The main function of a Monitoring Module (MM) is to perform continuous (or periodical) monitoring of selected machine component parameters in order to detect any anomalies in equipment operations. The simplest form of such a module may only perform threshold check on selected parameters. On detecting anomalies in the monitored parameters, the module may trigger one or more Health Assessment Modules, Diagnostics Modules or Prognostics Modules, synchronized by the SubMaSCoM. Alarms or further operations may be triggered based on the evaluation outputs of the SubMaSCoM.

(2) Health Assessment Module

The main function of a Health Assessment Module (HAM) is to perform assessment of the health status of a machine component being monitored. The following may trigger its operations: (1) an MM detects anomalies in monitored parameters and (2) the user (onsite or offsite) may request for an assessment to be performed on a specific set of data. Further operations may be triggered based on the evaluation outputs of the SubMaSCoM.

(3) Diagnostics Module

The main function of a Diagnostics Module (DM) is to identify/confirm the sources of machine component faults. The following may trigger its operations:



(1) an MM detects anomalies in monitored parameters and (2) the Machine Health Assessment Module detects signs of health degradation in monitored parameters. Further operations may be triggered based on the evaluation outputs of the SubMaSCoM.

**(4) Prognostics Module**

The main function of a Prognostics Module (PM) is to predict the future trends and the remaining useful life (RUL) of a machine component. It may access the historical records of component health status, which are required for forecasting machine component future trends. The following may trigger its operations: (1) a HAM/DM detects signs of degradation or operation deviations and (2) Pre-set schedules/periodic intervals to continuously predict future trends. Further operations may be triggered based on the evaluation outputs of the SubMaSCoM.

**(5) Maintenance Decision Support Module**

The main function of a Maintenance Decision Support Module (MDSM) is to provide support in terms of maintenance action recommendations. Its operations are typically based on available historical maintenance service records of the target equipment or other similar equipment/components (such as those stored in a 'Case database' used in the Case-based Reasoning technique (CBR)). The outputs may consist of the following: (1) options/recommendations for maintenance actions, (2) sets of corresponding risk factors/costs/confident levels of options/recommendations, and (3) maintenance operation instructions (with a list of required spare parts and tools).

**(6) Auxiliary Modules**

Auxiliary modules refer to a set of additional modules, which may be deployed to support other operations such as for doing some forms of raw data pre-processing, parameter estimation, assessment etc. They are not necessarily used for supporting maintenance operations. Instead, they may be used for other purposes such as for the assessment of equipment operations for design feedback etc. It may also include other future intelligent/automated support tools.

#### **5.3.6.7 Support Databases**

These support databases store two main categories of data/information: (1) a set of reference databases, which stores all data/information required by other modules such as system settings/configurations, schedules, modules/machine system components reference data/information etc and (2) a set of Knowledge databases, which stores data/information related to previous 'cases' or 'knowledge' of equipment faults/failures, used mainly by Diagnostics Modules (DMs), Prognostics Modules (PMs) and Maintenance Decision Support Modules (MDSMs) (e.g. for automatic reasoning).

#### **5.3.7 Machine Data Logger**

The Machine Data Logger (MDL) performs real-time data logging of selected component parameters. Figure 5.7 shows the components of an MDL and its relationships with other modules. Depending on the characteristics of parameters being monitored, data may be logged (i.e. sampled and digitised) at different frequencies (e.g. parameters with low change rates such as temperature may be logged at low sampling rates (Hz), while others with high change rates such as vibration signals may be logged at higher sampling rates (kHz or MHz)). A temporary data buffer is used to continuously (and temporarily) store data associated with selected parameters. Data in the buffer will be transferred to the Automated Maintenance and Reconfiguration Support System (AMaReSS) on request. In cases where equipment malfunctions, data is maintained in the buffer (including situations where equipment systems have completely shut down) until it is being transfer to the AMaReSS for further analysis. Unused data may then be 'flushed' after a pre-set time period. As shown in figure 5.7, an MDL may acquire data/information from either the equipment control system or directly from sensors or both.

## 5.4 Service Support Workflows

### 5.4.1 Introduction

This section (5.4) presents a discussion of how the proposed service support system provides support for the proposed strategy described in chapter 4. It is divided into five sub-sections (5.4.2 to 5.4.6), which describe the operation sequences (from the perspective of the roles of the service support system) for the different service support scenarios that correspond to those discussed in sub-section 4.4.2 to 4.4.6 of chapter 4. Note that a number of acronyms are used in figure 5.12 to 5.17, where: (1) CMMS stands for Computerised Maintenance Management System, (2) M/C stands for machine, (3) LC, AMaReSS, DIReSS and RMS<sup>3</sup> are components of the proposed service support system, details of which are presented in section 5.3.

### 5.4.2 Scenario 1: Diagnostics/Prognostics when equipment operation deviations/unexpected faults/failures are detected

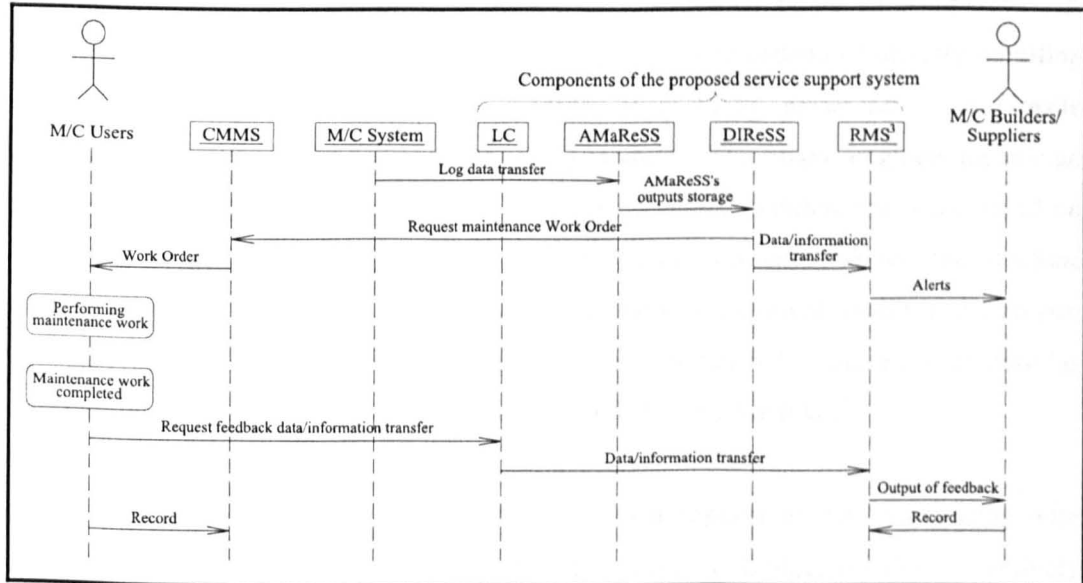


Fig. 5.12 Sequence diagram for an ideal service support process

In this scenario, the machine control system (or any other fault detection/safety mechanisms of the machine system) will trigger the Automated Maintenance and Re-configuration Support System (AMaReSS, which is responsible mainly for supporting the **Automated Maintenance Support** activity described in sub-section 4.3.2, chapter 4) when equipment operation deviations/unexpected faults/failures are detected. Ideally, the AMaReSS will provide all necessary support autonomously. It will provide onsite engineers/technicians with (ideally) accurate and comprehensive data/information (e.g. diagnostic/prognostic outputs and remedial action recommendations) to facilitate the planning and execution of maintenance work. Figure 5.12 illustrates a sequence diagram for such an ideal service support process. Note that in this case, the outputs of the Data/Information and Re-configuration Support System (DIRESS) are communicated directly to the Computerised Maintenance Management System (CMMS), which in turn will generate appropriate maintenance work orders. However, this would only be possible if a set of comprehensive and reliable automated maintenance-support-tools is available. In practice, the implementation of such scheme will need to be carried out incrementally over a period of time during the operational phase of equipment. A slightly different scenario, as depicted in figure 5.13, where instead of directly inputting the outputs of the DIRESS into the CMMS, it is being presented to the onsite engineer/technician via the Local Client (LC) module. The onsite engineer/technician will then make appropriate decision and plan for necessary maintenance work based on the provided data/information. Note that in both cases presented above, the machine builder/supplier is only acting as an 'observer', without active involvement in the service support process. In both cases, the machine builder/supplier will acquire and archive (as necessary) appropriate data/information via the DIRESS and the RMS<sup>3</sup>.

Figure 5.14 depicts a sequence diagram for a support process for dealing with more complex situations. In these cases, the machine builder/supplier is actively involved in the support process, particularly, in providing diagnostic, prognostic and maintenance decision support. The service support system (in particular, the following three main modules: the RMS<sup>3</sup>, DIRESS and AMaReSS) allows the machine builder/supplier to remotely access equipment data/information and to perform all necessary

analysis efficiently (as shown in the 'Detailed Analysis Phase' in figure 5.14). The RMS<sup>3</sup> and LC modules provide the necessary communication and information sharing tools. Maintenance action recommendations are fed back to the machine user via the LC module. If additional verification is required after the completion of a maintenance operation, the process could be performed remotely via the service support system as shown in the 'Further Verification and Feedback Phase' in figure 5.14.

In situations where remote re-configuration of the control system is feasible, the service support system allows the machine builder/supplier to perform the operation efficiently, as depicted in figure 5.15. As shown in the figure, the AMaReSS is responsible for the actual re-configuration operation. The RMS<sup>3</sup> and the LC module facilitate the coordination between the activities of the machine user and the machine builder/supplier.

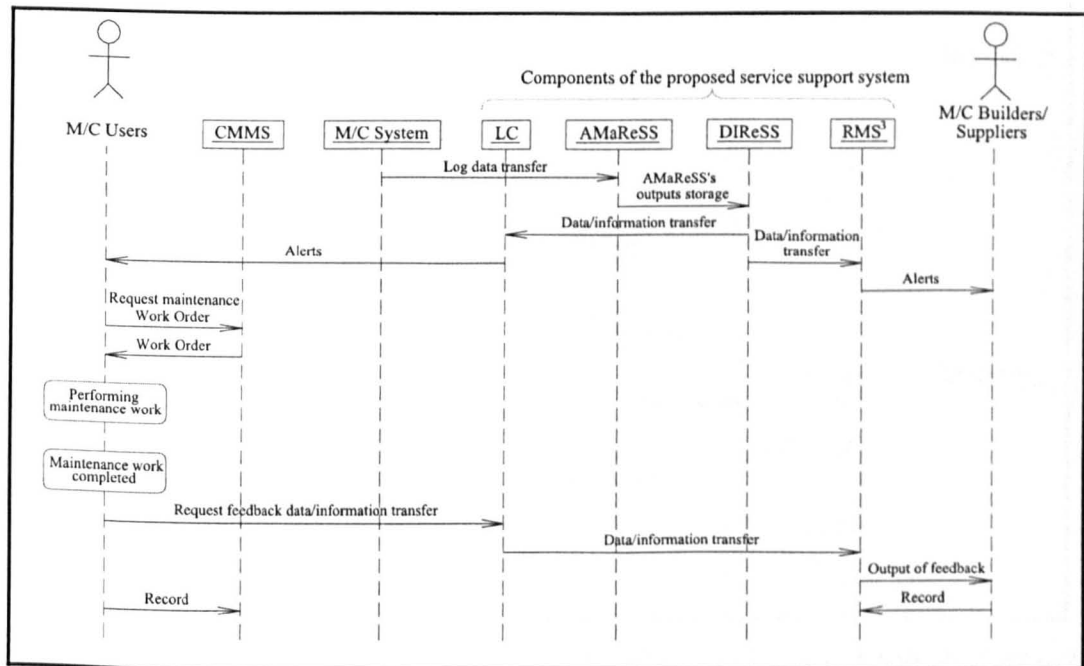


Fig. 5.13 Sequence diagram for a typical service support process without the active involvement of machine builders/suppliers

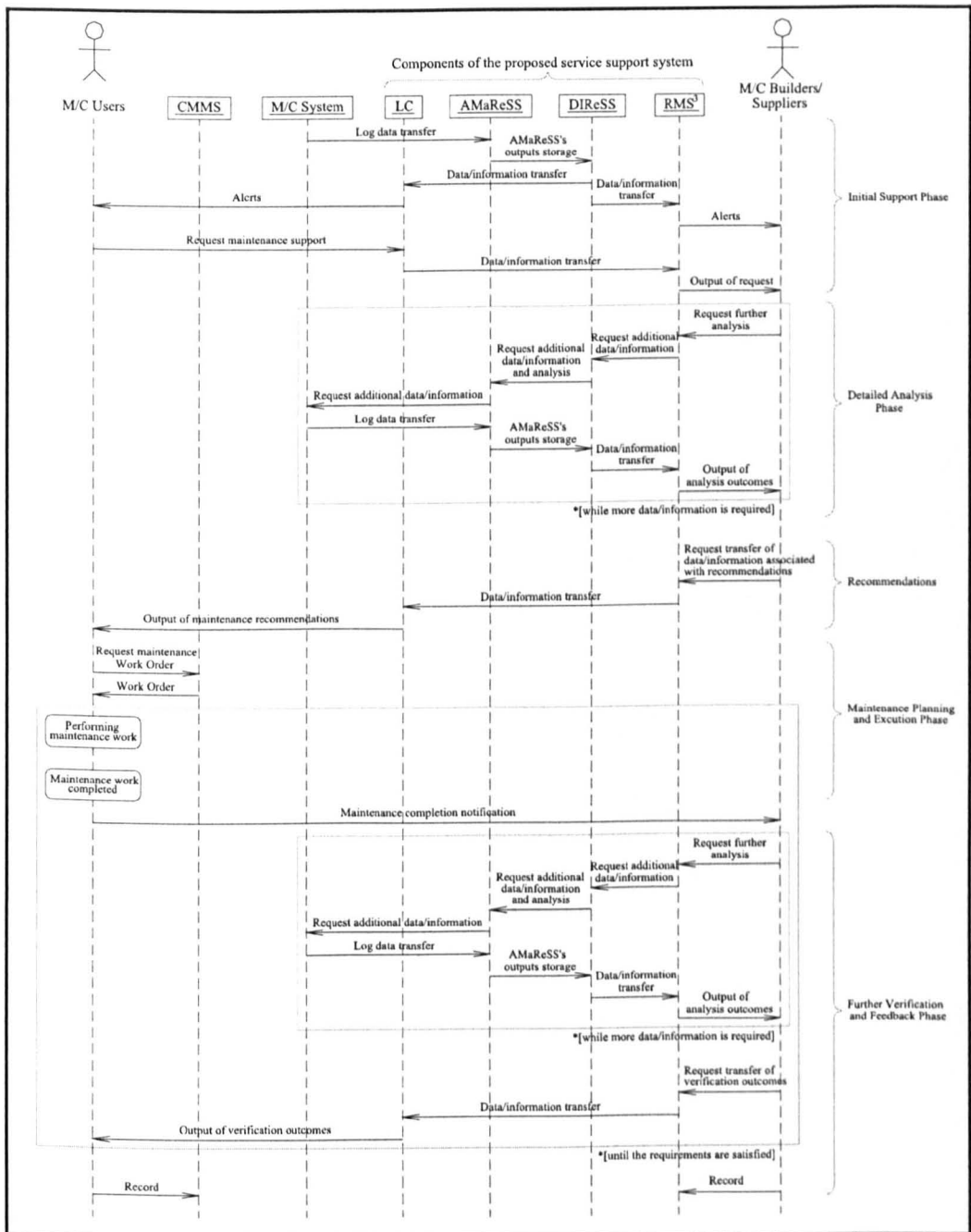
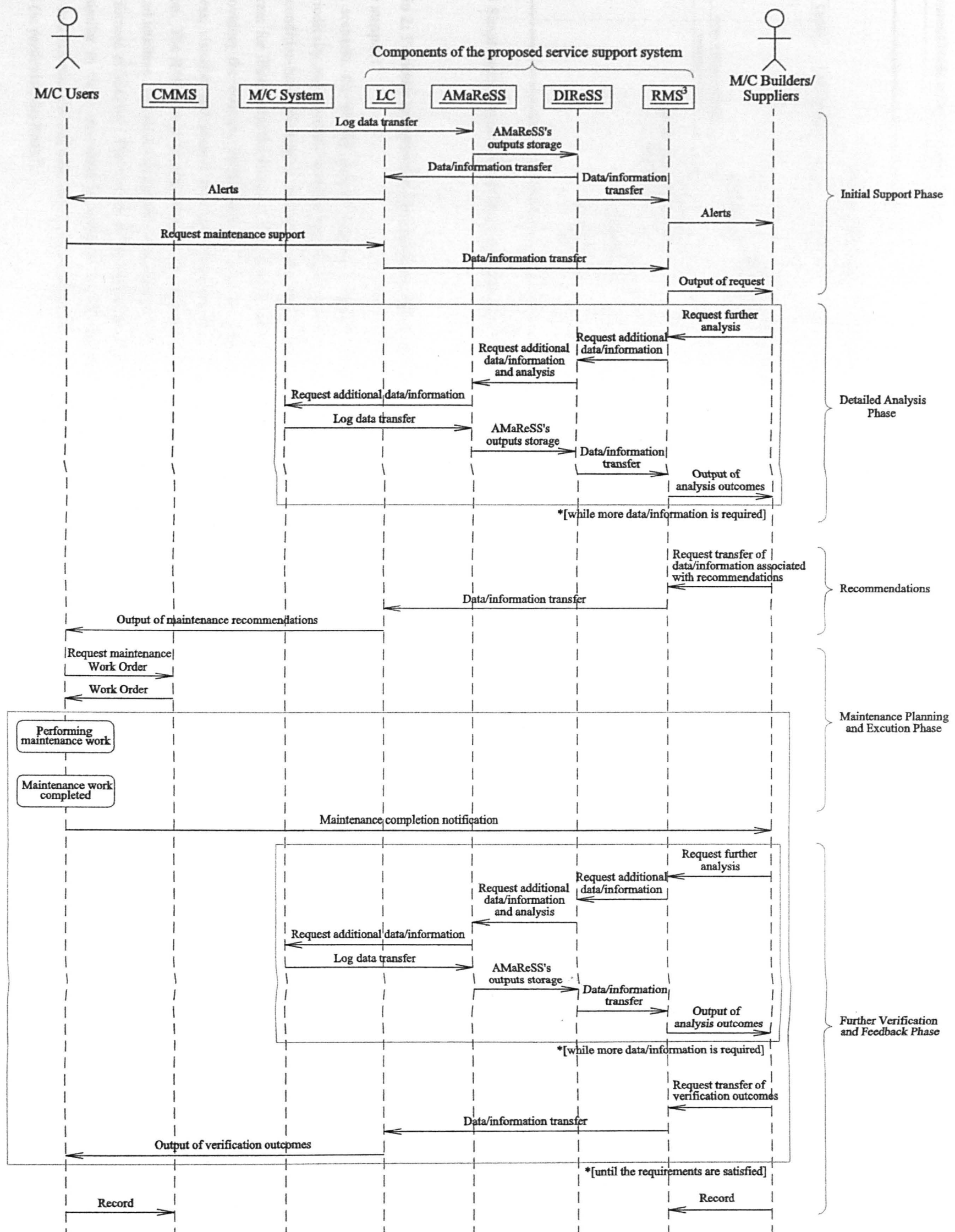


Fig. 5.14 Sequence diagram for a typical service support process with active involvement of machine builders/suppliers (Please refer to the following page (A3) for an enlarged copy of this figure.)



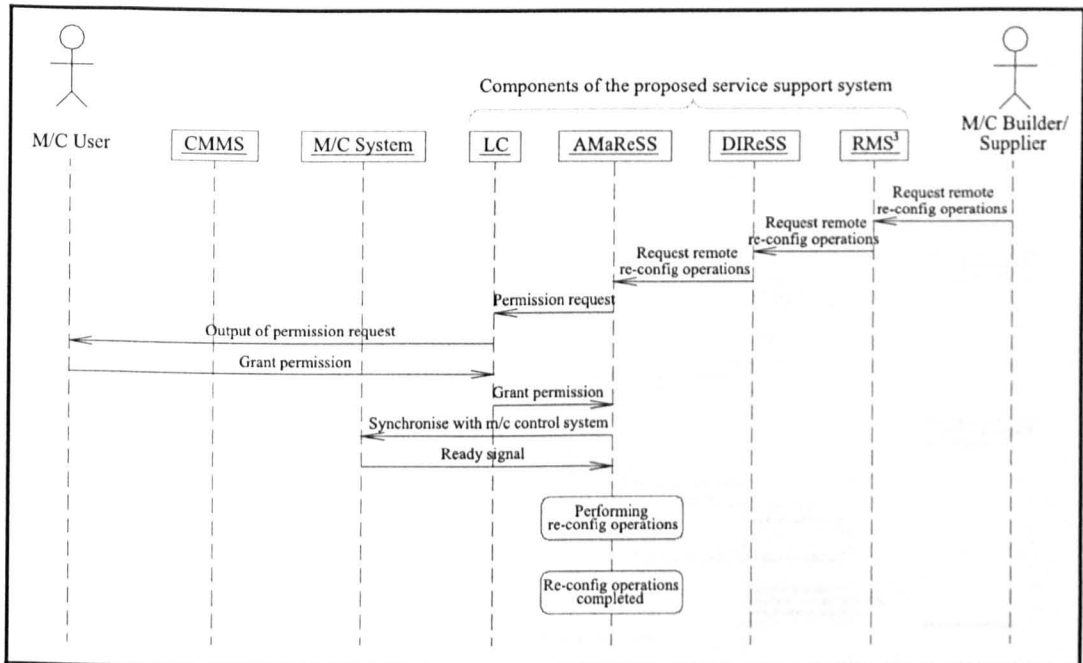


Fig. 5.15 Simplified sequence diagram for a typical re-configuration operation

### 5.4.3 Scenario 2: Periodic monitoring for condition-based preventive maintenance support

In this scenario, the service support system is used by the machine builder/supplier to periodically and remotely monitor equipment operation status and to predict future trends (condition-based preventive maintenance). Figure 5.16 shows a simplified sequence diagram for illustrating the process. The service support system supports the process by providing the machine builder/supplier with an integrated set of tools to efficiently access, visualise and analyse both current and archived historical equipment data/information. The RMS<sup>3</sup>, in particular, provides the machine builder/supplier with a user-friendly and intuitive 3D-based visualization and analysis environment, allowing the tasks to be performed efficiently. The outputs of the analysis process will then be used for purposes similar to those described in scenario 1 (See sub-section 5.4.2.). All useful/relevant data/information will then be archived using tools provided by the service support system (in particular, the RMS<sup>3</sup>).



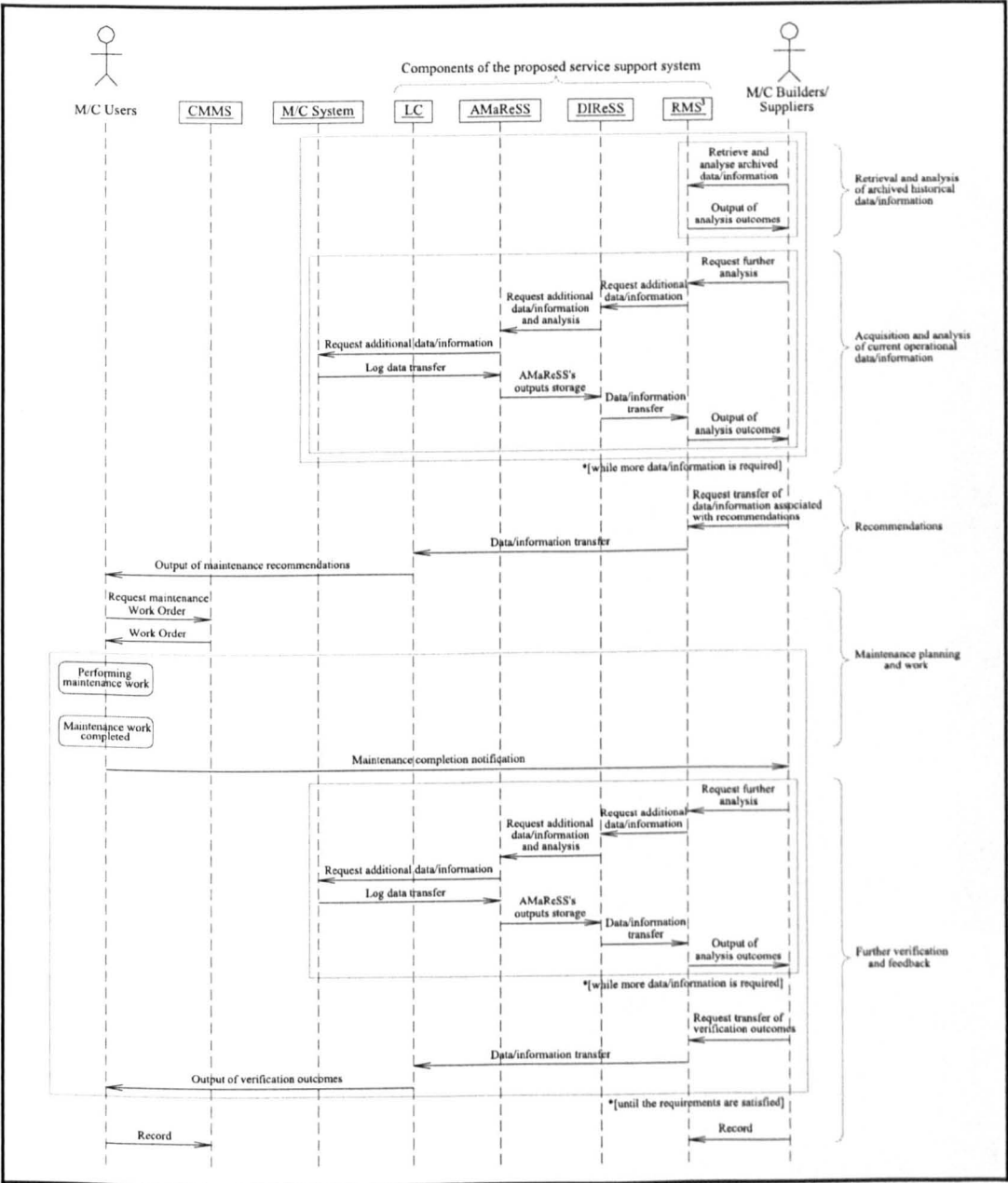
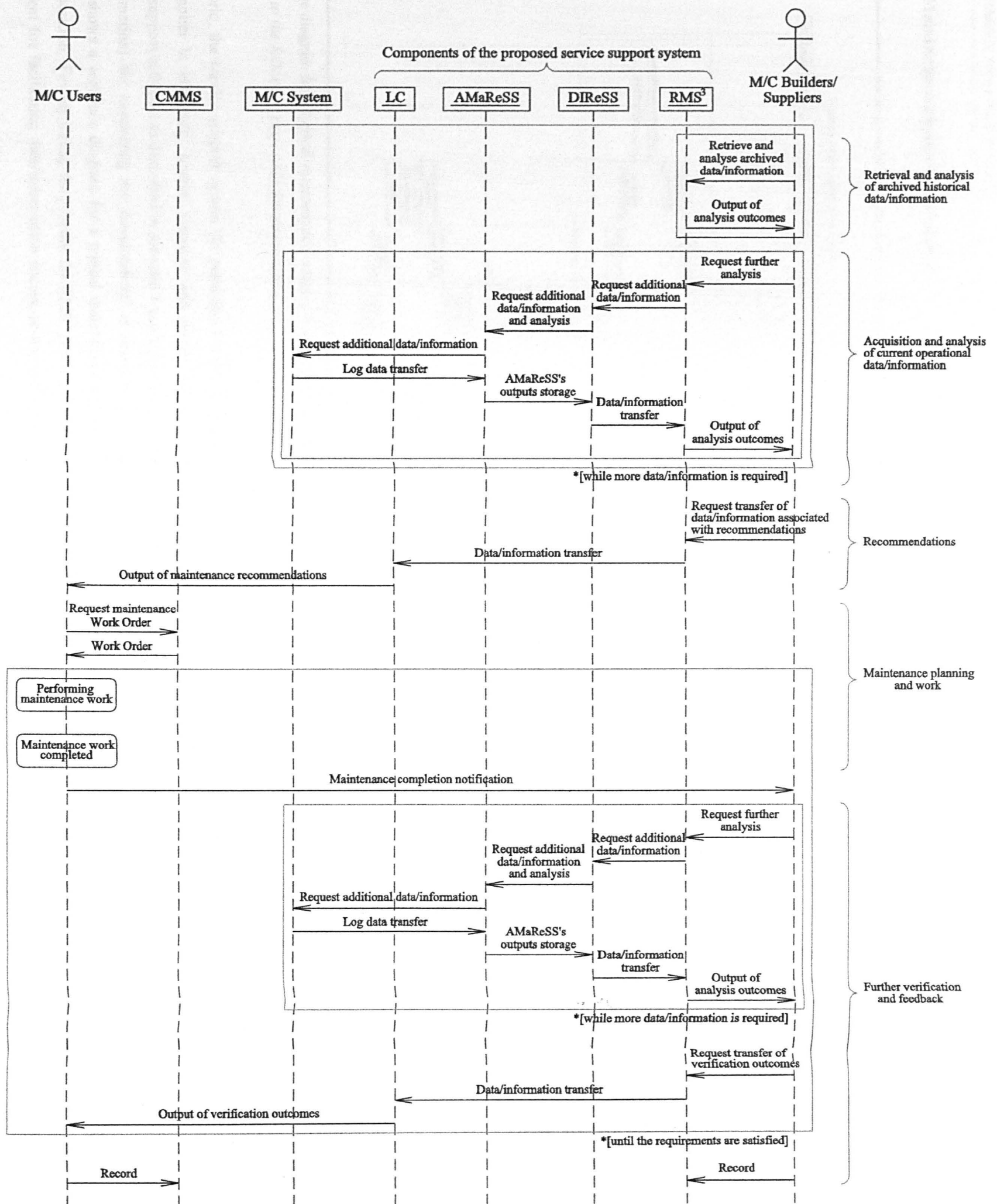


Fig. 5.16 Sequence diagram for scenario 2 (Please refer to the following page (A3) for an enlarged copy of this figure.)



#### 5.4.4 Scenario 3: Maintenance-support-tool support

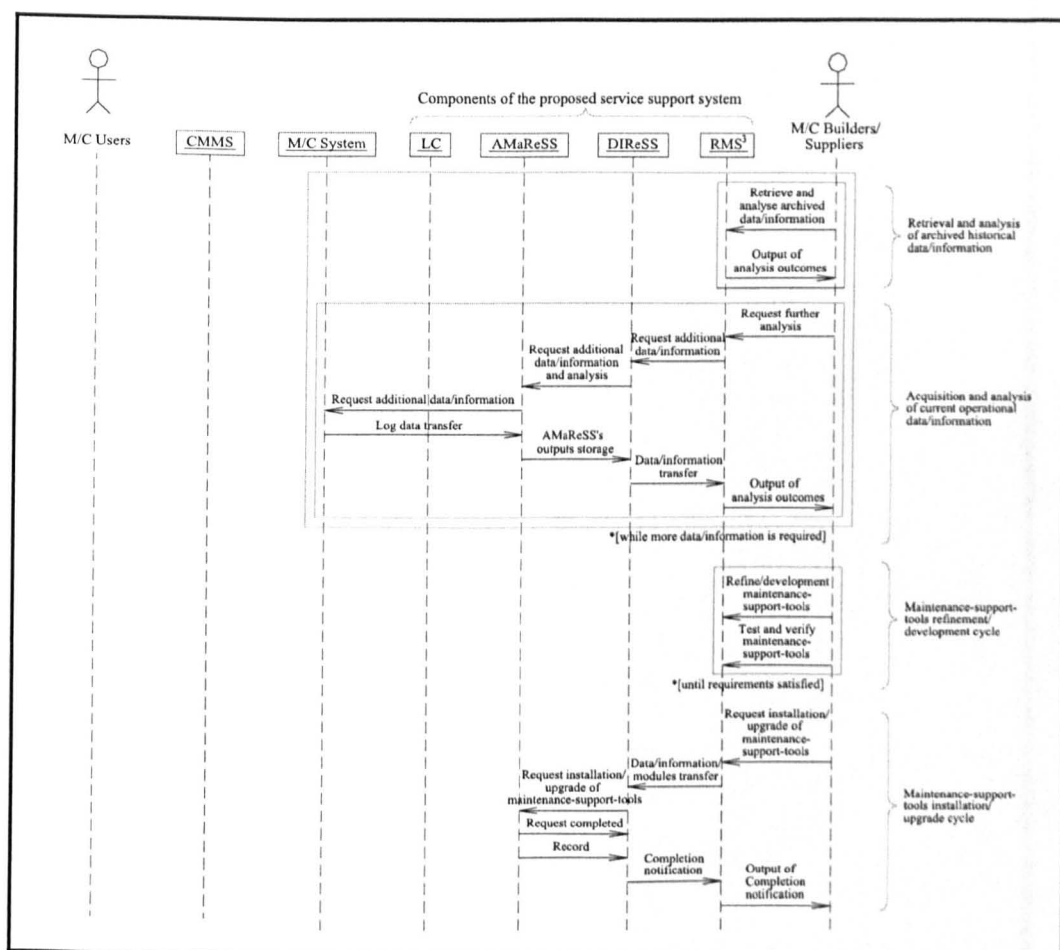
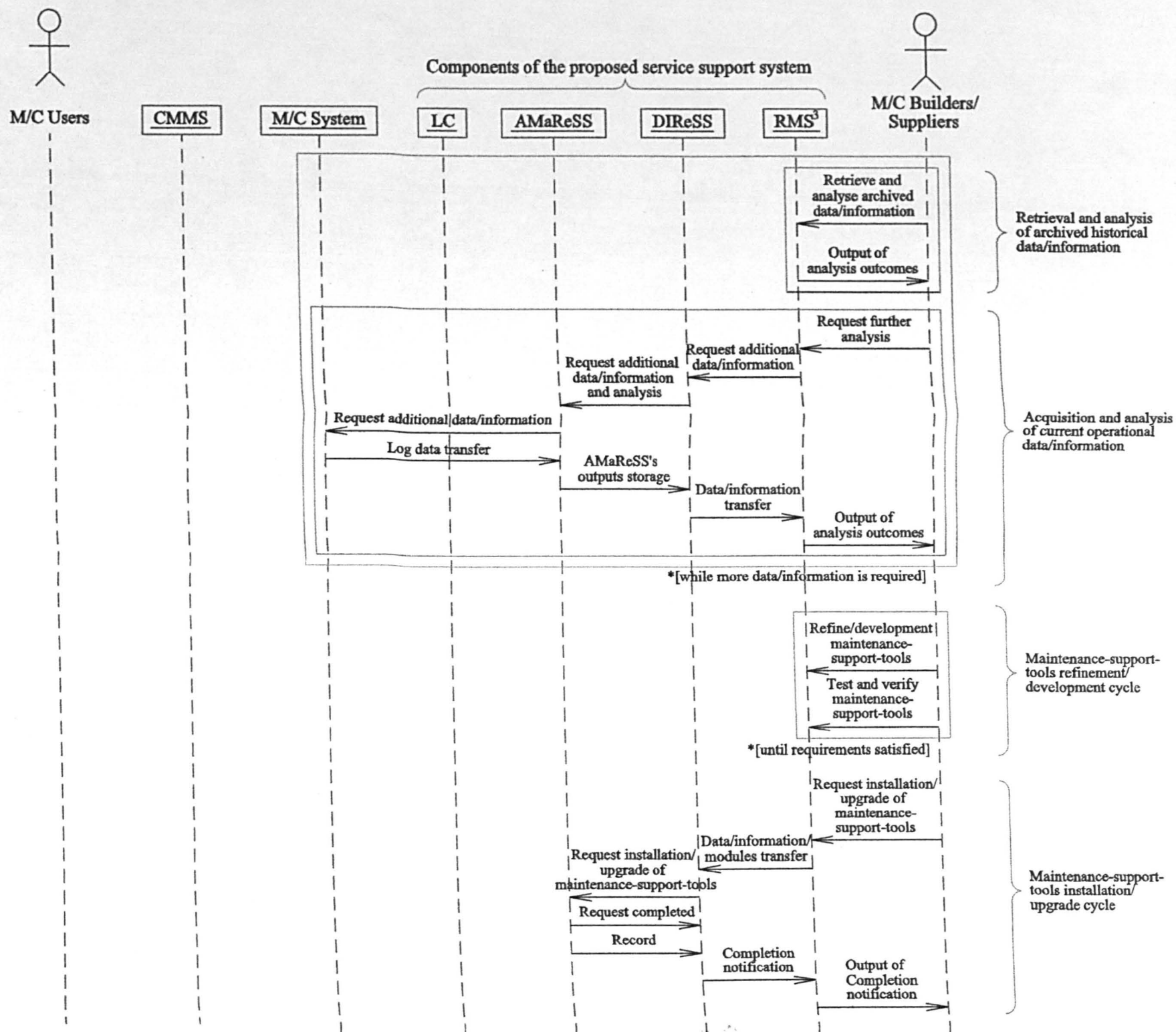


Fig. 5.17 Sequence diagram for a typical maintenance-support-tool support operation  
(Please refer to the following page (A3) for an enlarged copy of this figure.)

In this scenario, the service support system (in particular the RMS<sup>3</sup>) allows the machine builder/supplier to efficiently access, visualise and re-use data/information acquired during the support activities as described in scenario 1 and 2 (including archived historical data/information) for supporting the development of maintenance-support-tools. Figure 5.17 shows a sequence diagram for a typical maintenance-support-tools/strategies support operation. For supporting the process, the RMS<sup>3</sup> provides an integrated 3D-based environment for facilitating data/information access, re-use and sharing with



other support tools such as data analysis and software development tools. It allows various maintenance-support-tool/strategy support activities such as support tool development, testing, assessment, improvement, refinement and optimisation to be performed remotely and efficiently. Once it is verified that the required level of performance has been achieved, the maintenance-support-tools (software modules) could then be deployed (installed) remotely with the assistance of the DIReSS and the AMaReSS, as illustrated in figure 5.17. The service support system also allows remote support for installed maintenance-support-tools (which are embedded in the control system of equipment) to be provided efficiently.

#### **5.4.5 Scenario 4: Design feedback**

In this scenario, the service support system (in particular the RMS<sup>3</sup>) provides the machine builder/supplier with tools to efficiently access, visualise and analyse data/information acquired during the support activities as described in scenario 1 and 2 for supporting design feedback operations. For supporting the process, the RMS<sup>3</sup> provides an integrated 3D-based environment for facilitating data/information access, re-use and sharing with available design support tools allowing the performance of equipment to be assessed efficiently. Any recommendations will then be fed back to the machine user via a similar sequence as depicted in figure 5.14 (scenario 1) and figure 5.16 (scenario 2). In addition, the RMS<sup>3</sup> also provides tools for efficient archiving of all useful/relevant data/information for other support activities and future reference.

#### **5.4.6 Scenario 5: Equipment re-configuration, upgrade and expansion support**

The main module used in this scenario is the RMS<sup>3</sup>. In this case, the RMS<sup>3</sup> provides a 3D-based virtual prototyping environment where an equipment re-configuration/upgrade/expansion operation could first be carried out 'virtually'. It allows the machine builder/supplier to experiment with various potential/new configurations/changes to existing equipment system in order to meet new customer requirements. It also provides tools for efficient access and re-use of archived data/information, which ideally would speed up the design process. The virtual prototypes could also be used for

customer interface, via the LC module. Once a new configuration is verified 'virtually', re-configuration/upgrade/expansion operation planning could then be performed in the same virtual environment. Subsequently, by integrating the environment with appropriate simulation/emulation tools, the reconfiguration/upgrade/expansion of the equipment software system could then be performed offsite. In conjunction with the operation, the onsite hardware re-configuration/upgrade/expansion operation and offsite maintenance-support-tool re-configuration operation could also be performed. The RMS<sup>3</sup> and the LC module are used to facilitate coordination between onsite and offsite operations. Any further monitoring and verification could be performed (onsite/offsite) via the service support system during/after the completion of a re-configuration/upgrade/expansion operation.

## 5.5 Chapter Summary

This chapter has presented a detailed description of a 3D-based advanced machine service support system proposed for supporting the service support strategy presented in chapter 4. It has presented a set of main requirements for the proposed service support system. It then presented a detailed discussion of a reference architecture for the proposed support system. The proposed support system is based on the integration of a 3D-based virtual environment with a set of re-configurable modular automated maintenance-support-tools (which is embedded in the real machine system), a maintenance-support-tools/strategies support environment and an equipment re-configuration/upgrade/expansion support environment, in a network/Internet framework. For illustrating how the proposed system provides support for the advanced service support strategy advocated, five scenarios have been presented (which correspond to those presented in section 4.4 of chapter 4). The next chapter (chapter 6) presents a detailed description of the design and implementation of a prototype for demonstrating the main concepts of the proposed 3D-based service support system/strategy presented in this chapter and chapter 4.

## **Chapter 6**

# **Design and Implementation**

### **6.1 Introduction**

This chapter presents a description of the design and implementation of a prototype for demonstrating the main concepts of the proposed 3D-based Advanced Machine Service Support System/Strategy. First, section 6.2 presents a brief description of a test bed, at the Mechatronics Research Centre, De Montfort University, UK, used for this study. This is followed by section 6.3, which presents a detailed description of a prototype, developed based on the proposed reference architecture described in chapter 5. Lastly, section 6.4 presents a summary of this chapter.

### **6.2 Test Bed**

#### **6.2.1 Introduction**

The test bed consists of a flexible conveyor system, with the Smart Distributed System (SDS) based control (Honeywell, 2005), an Automated Guided Vehicle (AGV), with the Local Operating Network (LON) based control (Echolen, 2005), a SCARA robot and a gantry robot, both with the NextMove PC-based control (Baldor Electric, 2005). The test cases conducted in this research are based mainly on the SCARA robot and the flexible conveyor system. The following sub-sections (6.2.2 and 6.2.3) present a brief description of the two devices.

#### **6.2.2 SCARA Robot**

The SCARA robot is a 4-axis robot retrofitted with a PC-based motion control system. Figure 6.1 shows a view of the robot. It consists of three rotational axes, a vertical axis and a pneumatic gripper (currently not used). The approximate operating ranges of the axes are as follows:

- i. Axis 1,  $+180^\circ$
- ii. Axis 2,  $\pm 120^\circ$
- iii. Axis 3,  $\pm 180^\circ$

iv. Axis 4, +20mm/-70mm

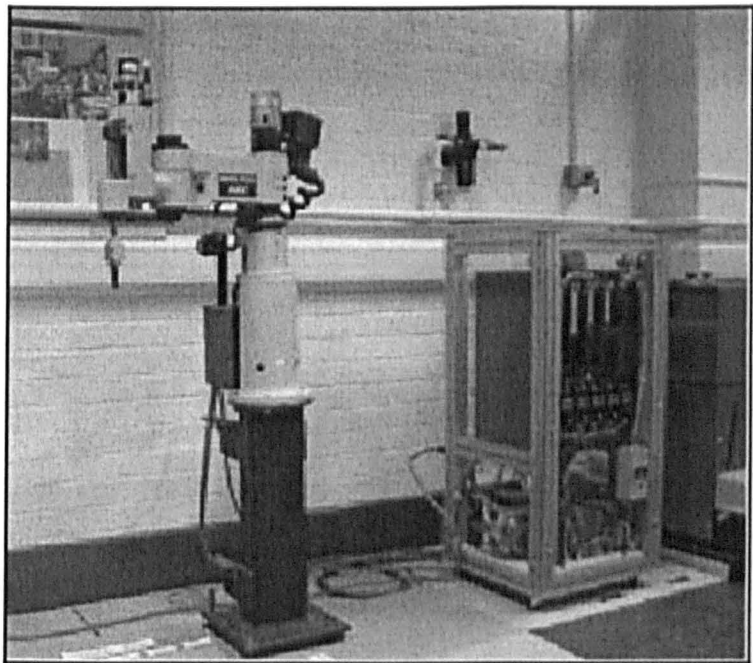


Fig. 6.1 SCARA robot

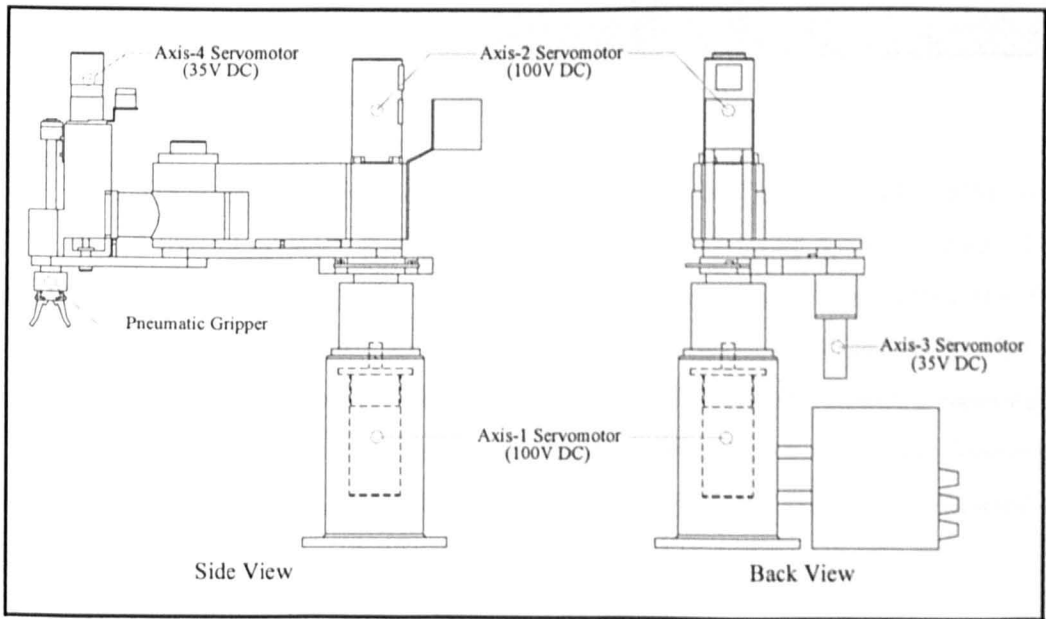


Fig. 6.2 Component layout of the SCARA robot



Each axis is driven by an electric DC servomotor, with axis 1 and 2 driven by 100V DC servomotors, while Axis 3 and 4 are driven by 35V DC servomotors, as depicted in figure 6.2. The servomotors are controlled by a NextMove PC-based 4-axis PID motion controller, with a Windows-based control application (software), developed in-house.

### 6.2.3 Flexible Conveyor System

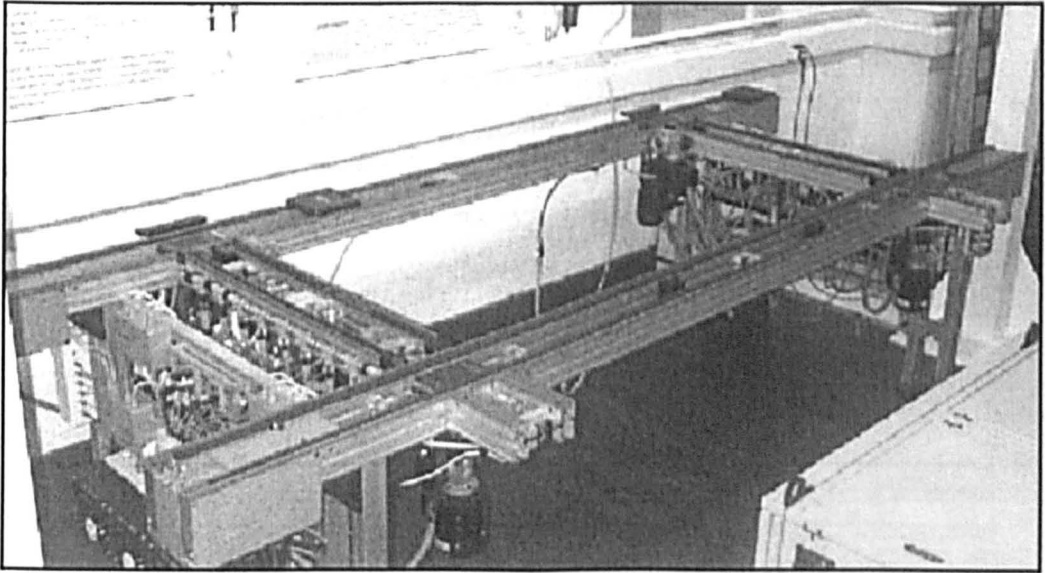


Fig. 6.3 Flexible conveyor system

The conveyor system was originally manufactured by Bosch (Bosch, 2005), with a PLC-based control system. It was retrofitted with an SDS-based control system. The SDS (Smart Distributed System) is a CAN-based bus system, from Honeywell's MICRO SWITCH DIVISION, designed for facilitating the distributed control and integration of intelligent actuators and sensors. For more details on SDS, see Honeywell (Honeywell, 2005). Figure 6.3 shows a view of the conveyor system. It consists of the following actuators modules (either manufactured by Bosch or fabricated in-house), as depicted in figure 6.4:

- 2 Longitudinal Conveyors (LCs)
- 2 Transverse Conveyors (TCs)

- 4 Lift Transfer Units (LTUs)
- 2 Lift Rotate Position Units (LRPUs)
- 7 Rotary Stop Gates (RSGs)
- 4 Interchangeable Stop Gates (ISGs)

The control system consists of a PC-based PCI SDS controller, on the Windows NT platform; with the Think & Do control software (Entivity, 2005). Figure 6.5 depicts the component layout of the SDS-based control network. In general, it consists of the following components (switches, valves and sensors):

- 17 SDS-based Solenoid Valves (SVs)
- 8 SDS-based 3-phase Motor Starters (MSs) (for 3-phase asynchronous AC motors driving the conveyors)
- 14 SDS-based Photoelectric Sensors (PESs)
- 1 SDS-based Emergency Switch
- 1 SDS-based Main Switch

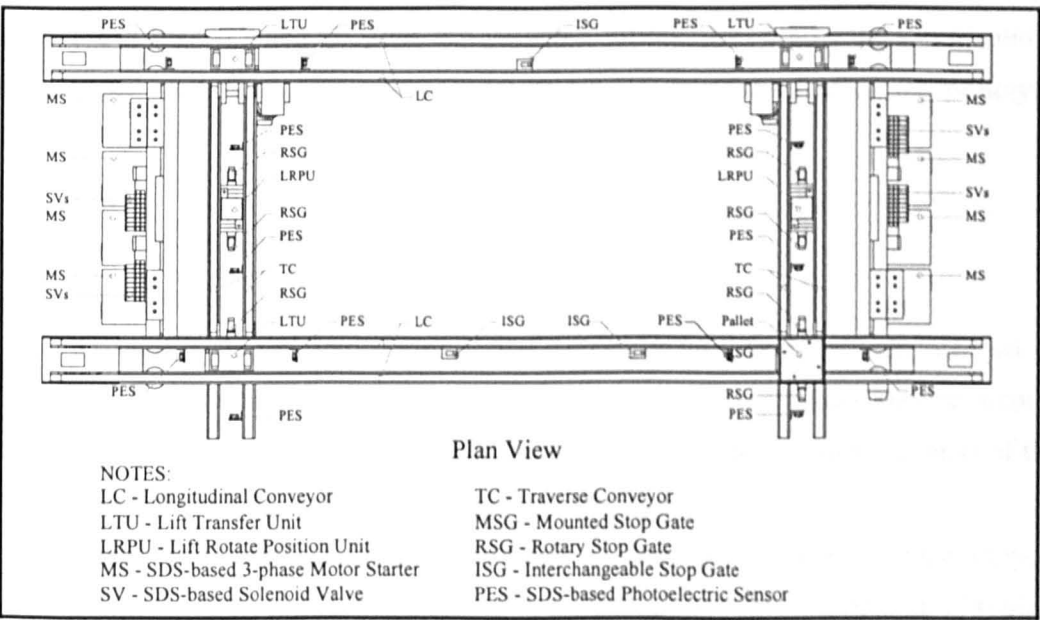


Fig. 6.4 Component layout of the flexible conveyor system

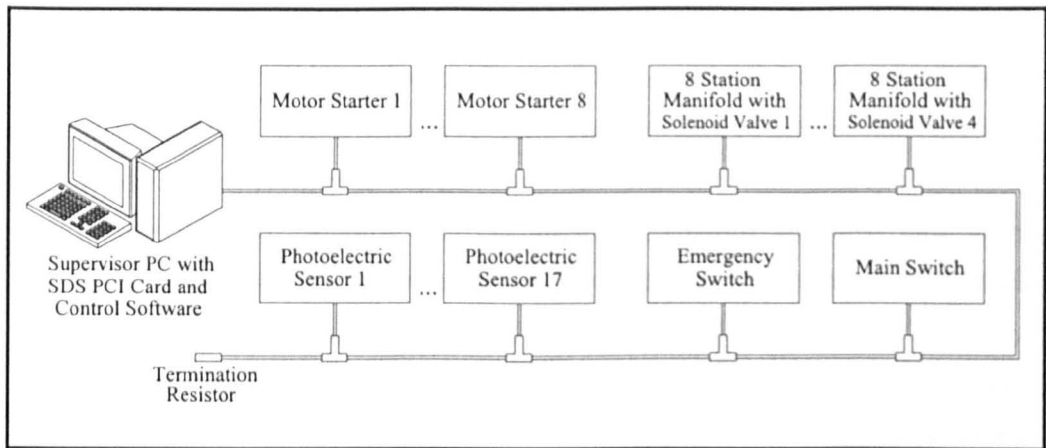


Fig. 6.5 Component layout of the SDS-based control network

## 6.3 Prototype

### 6.3.1 Introduction

This section (6.3) presents a detailed description of a prototype developed for the demonstration of the main concepts of the proposed service support system/strategy (presented in chapter 4 and 5). First, sub-section 6.3.2 describes briefly the specifications of the prototype. Then, sub-section 6.3.3 and 6.3.4 describe in detail the prototype hardware and software elements.

### 6.3.2 Prototype Specifications

#### 6.3.2.1 Introduction

The prototype has been designed and developed to provide an integrated set of software toolsets/modules that allow the various concepts of the proposed service support system/strategy to be demonstrated and evaluated. It allows the following aspects of the proposed system/strategy to be demonstrated and explored:

- (1) It provides tools for the demonstration of how the proposed service support system/strategy can facilitate access to the operational data/information of typical manufacturing equipment, allowing the status of equipment to be monitored efficiently.

- (2) It provides tools for the demonstration of how various types of equipment operational data/information can be acquired, organized, transferred, reorganized, visualized and re-used efficiently. The various types of data/information include the following categories: (1) motion-related analogue data such as displacement, velocity and acceleration etc, (2) non-motion-related analogue data such as voltage, current, temperature, pressure etc, (3) digital state such as switch/transducer states, actuator states, digital on/off control signals etc.
- (3) It allows the demonstration of how the proposed service support system/strategy can improve remote machine monitoring, diagnostics and prognostics, based on (1) and (2) above.
- (4) It allows the demonstration of how the tasks of machine design feedback such as design verification, design flaw identification and knowledge/experience capture can be performed remotely, based on (1) and (2) above.
- (5) It allows the demonstration of how the proposed service support system/strategy can be integrated with automated maintenance-support-tools and in particular, how it can facilitate remote support for automated maintenance-support-tools.
- (6) It allows the demonstration of how the proposed service support system/strategy can facilitate in-service equipment re-configuration/upgrade/expansion support for manufacturing equipment.

#### **6.3.2.2 General Specifications**

The developed prototype consists of a set of integrated modular network-ready software toolsets (Note that this sub-section presents only a brief discussion of the specifications, as most related details will be presented in sub-section 6.3.4.), consisting of the following main modules:

- (1) An Integrated 2D/3D Visualisation and Analysis Module (IVAM), the main application module, which provides an integrated 2D/3D virtual environment, where users can gain access to equipment data, information and tools required to set up and perform all tasks relevant to performing machine service support functions.

- (2) A set of Support Tools Library Server Modules (STLS), responsible for providing various data analysis support tools for the IVAM.
- (3) A Communication Proxy Module (CPM), which serves as a communication agent to the IVAM, managing all communication details with the Data/Information and Re-configuration Support Server Module (DIReSSM, see (4) below.).
- (4) A Data/Information and Re-configuration Support Server Module (DIReSSM), which provides an application interface for accessing equipment log databases.
- (5) A set of Automated Maintenance and Re-configuration Support Modules (AMaReSM), which performs automated monitoring and re-configuration support functions for both the control system and the maintenance-support-tool.
- (6) A set of Machine Data Logger Modules (MDLM), which perform data acquisition and logging functions. This module provides an abstraction layer allowing data to be acquired from different sources by maintaining a common communication interface for the DIReSSM and AMaReSM.

#### **6.3.2.3 General Non-Functional Specifications**

- (1) The toolsets were designed to run on a PC platform, with either a Windows 2000 or Windows XP operating system.
- (2) They were designed to make use of existing facilities whenever possible (both software and hardware), allowing them to be used on existing facilities without requiring major changes to these facilities and minimizing the need for special purpose facilities.
- (3) They were designed to be as modular as possible to facilitate future upgrade. Each module is, generally, loosely coupled (but tightly integrated) with each other via, mostly TCP/IP-based communication links.
- (4) They make full re-use of existing design CAD data and other relevant design data/information without requiring such data/information to be re-created for allowing them to be used with the toolsets.
- (5) They were designed to be as user-friendly as possible, based on a typical Windows application user interface.

#### **6.3.2.4 Security-related Specifications**

The toolsets should satisfy the following security-related requirements for Internet communication. However, the current version of the prototype has not included this functionality, which would be included in the future version. The requirements are:

**(1) Sufficient Authentication**

An appropriate mechanism should be provided for authenticating clients' (the Communication Proxy Module – CPM) identities. The Data/Information and Re-configuration Support Server Module (DIRESSM) should maintain appropriate information and should not allow its clients to directly access this information, remotely. All security-related information must be stored in a 'non-human-readable' form (refer to the following section), in a database local to the Data/Information and Re-configuration Support Server Module (DIRESSM).

**(2) Data Storage and Transmission Security**

All sensitive data/information must be stored and transmitted in encrypted form based on a proven encryption algorithm. A 'simple' encryption algorithm may be acceptable for the transmission of logger data (in order to minimize data transmission overheads). An appropriate 'data hashing' mechanism should be provided to ensure 'originality' of data transmitted. In addition, appropriate mechanisms for detecting, identifying and correcting faults due to transmission errors should also be provided.

**(3) Compatible with the Security Requirements of existing Facilities**

The toolsets must be designed to be compatible with the security requirements of existing facilities, i.e. their deployment should not require major adjustments to the security configurations of existing facilities.

### 6.3.3 Hardware Implementation

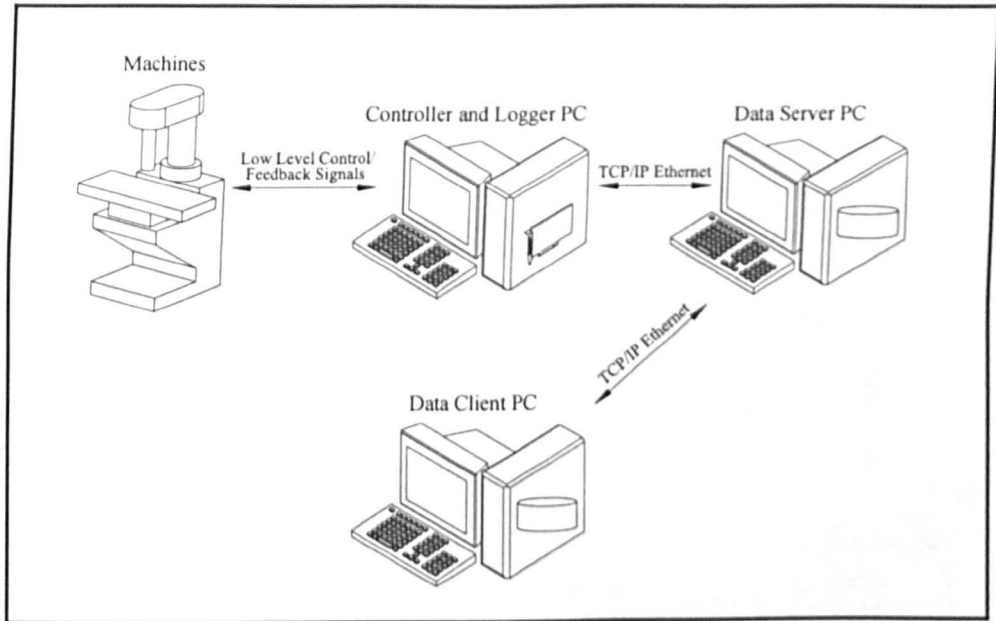


Fig. 6.6 Prototype hardware configuration

The prototype consists of the following hardware components, as depicted in figure 6.6: (1) a 4-axis SCARA Robot and a conveyor system, (2) a PC (the Controller and Logger PC of figure 6.6) hosting a PC-based motion controller, which (the PC) is also running a Machine Data Logger Module (MDLM), (3) a PC (the Data Server PC of figure 6.6) running a Data/Information and Re-configuration Support Server Module (DIReSSM), this PC is also hosting an Automated Maintenance Support Module (AMaReSM) and (4) a PC (the Data Client PC of figure 6.6) running an Integrated 2D/3D Visualisation and Analysis module (IVAM) with other additional modules. All the PCs are linked in a Transmission Control Protocol/Internet Protocol-based (TCP/IP-based) Ethernet local area network.

### 6.3.4 Software Implementation

#### 6.3.4.1 Introduction

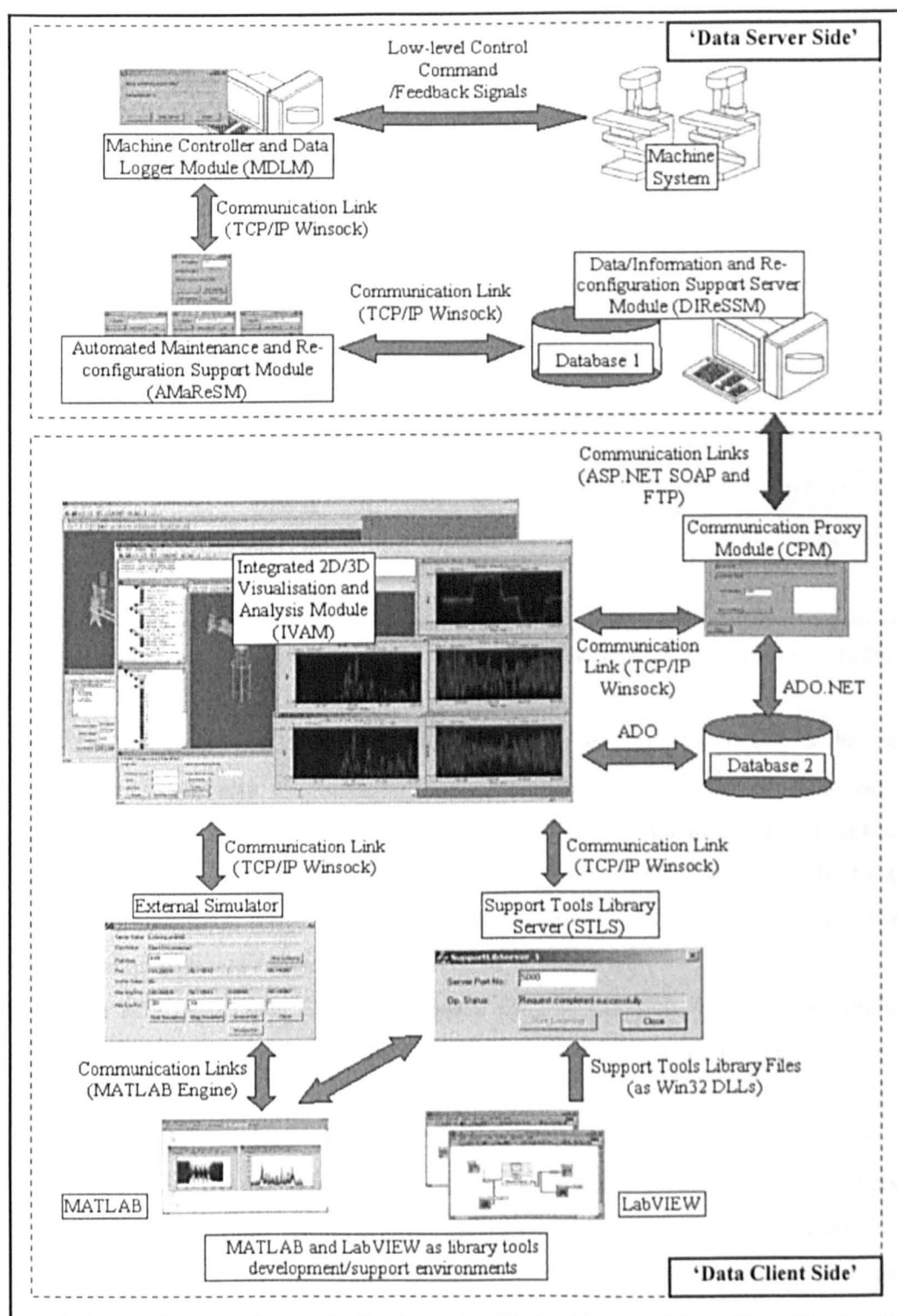


Fig. 6.7 Configuration of prototype software modules



The prototype software consists of a set of highly integrated network-ready modules, distributed across a local area network. Figure 6.7 shows an overview of the prototype software modules. The following sub-sections present a detailed description of each of the modules.

6.3.4.2 Integrated 2D/3D Visualisation and Analysis Module

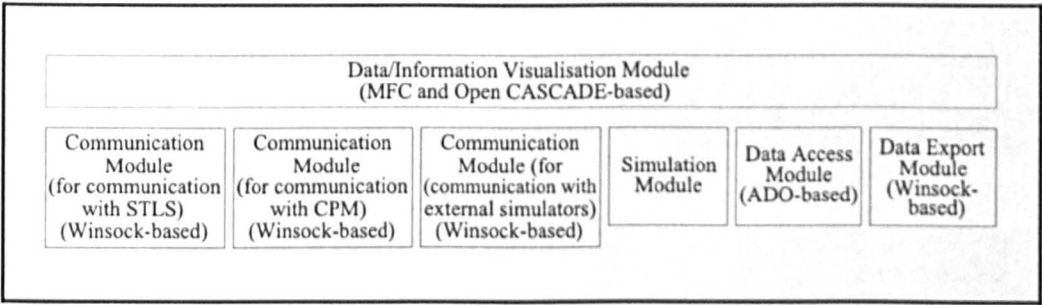


Fig. 6.8 Main components of the Integrated 2D/3D Visualisation and Analysis Module

The Integrated 2D/3D Visualisation and Analysis Module (IVAM) is the main module, which provides an interactive 3D-based user interface for users to access equipment data/information and support tools. The module is a Win32 application based on the Microsoft Foundation Class (MFC) Library Version 6.0 (Microsoft, 2005) and Open CASCADE CAD Kernel Version 5.1 (Open CASCADE, 2003). It consists of the following main software components, as depicted in figure 6.8:

- (1) An MFC and Open CASCADE-based Data/Information Visualisation Module, which provides the main visualization interface for interaction with the virtual model of the equipment being monitored.
- (2) A set of Winsock-based (TCP/IP) Communication Modules, which are responsible for managing communication with the Support Tools Library Server (STLS), the Communication Proxy Module (CPM) and external simulators.
- (3) A Simulation Module, which is responsible for performing graphic simulation functions.

- (4) An ActiveX Data Objects-based (ADO-based) Data Access Module for managing all details related to local database access.
- (5) A general purpose Winsock-based (TCP/IP) Data Export Module for facilitating data sharing with other data analysis and software development environments such as MATLAB etc.

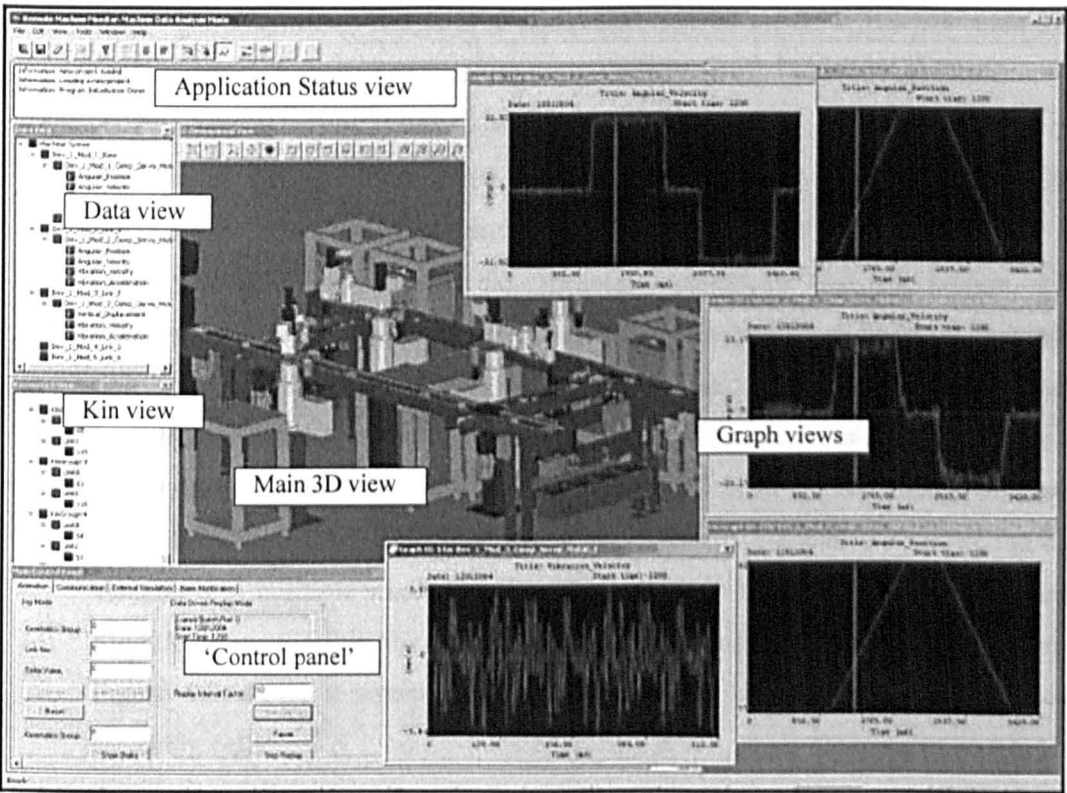


Fig. 6.9 User interface of the Integrated 2D/3D Visualisation and Analysis Module

The visualization module consists of a set of integrated (interactively-linked) 2D/3D visualization windows allowing various data/information to be visualized in an intuitive manner. Figure 6.9 shows a screen shot of the main user interface of the Integrated 2D/3D Visualisation and Analysis Module (IVAM). As shown in the figure, the user interface consists of the following windows:

- (1) A ‘tree-view’ showing equipment data structures. It provides users with a ‘context-sensitive’ environment for accessing archived historical log data/

information and support tools associated with each component parameter. The support tools are provided via a Support Tools Library Server (See sub-section 6.3.4.4 for details.). It also provides additional access links to other archived equipment data/information such as component manufacturer technical data/information, additional CAD data, web resources etc.

- (2) A 'tree-view' showing equipment kinematics structures (the Kin View in figure 6.9). The kinematics structure of equipment can be set up within the main 3D environment via a set of kinematics set-up tools (See (3) below for details.).
- (3) A 3D graphic visualisation window presenting the 3D geometric model of equipment. The 3D visualisation environment is based on the Open CASCADE CAD Kernel Version 5.1 (Open CASCADE, 2003). It provides users with a context-sensitive environment for accessing equipment data/information and support tools such as data source set-up tools, kinematics set-up tools, graphic objects manipulation tools, data analysis tools etc. It also provides a virtual environment for the 'replay' of 'recorded' equipment historical events. During a replay, the environment animates changes in parameters, with respect to time, using archived historical data/information. Animated outputs of a replay can be visualized in multiple windows/views (both 2D and 3D-based). The Simulation Module is responsible for synchronizing the simulation step in all windows. Figure 6.9 shows a screen shot of the animation of a historical event of an assembly cell.
- (4) A 'multi-page' control panel, providing users with interfaces for accessing animation/simulation support tools, communication support tools, interfacing tools and service support reporting tools.
- (5) An array of 2D graphic visualization windows, which present equipment data in the form of graphs/charts. These views are synchronised with the main 3D view during animation allowing various inter-related data to be visualized effectively, as shown in figure 6.9.

It has three operational modes, namely: (1) the Setup Mode, (2) the Data Transfer Mode and (3) the Simulation and Analysis Mode (the default mode):

- (1) In the Setup Mode, the environment provides tools for setting up the environment for the purpose of preparing the original CAD models of an equipment system (created during the design phase) to be used for machine support tasks. The set of tools consist of:
  - (a) Tools for project management, consisting of tools for organizing, loading and storing project data. It also provides a translator tool for importing and translating 3D CAD data from major commercial CAD systems. The current version supports only the STEP format (the Standard for the Exchange of Product).
  - (b) Tools for setting up the graphical properties of 3D graphic objects, which form the virtual models of a real equipment system. The provided toolset consists of: (1) tools for setting the transparency level, (2) tools for setting the colors and (3) tools for setting the rendering modes, of 3D graphic objects.
  - (c) Tools for setting up project data structures, which includes configuration tools for creating new data objects (each of which is linked to a specific 3D graphic object in the 3D environment), tools to set up connections with a single or a group of databases, data tables, data fields and selected data ranges etc.
  - (d) Tools for setting up the kinematics structure of a virtual model, which consist of a set of configuration tools for defining and creating new kinematics groups and to add new kinematics links. The current version of the tools is capable of setting up new kinematics structures of the type 'Serial Open Link' (of either linear, rotational or a mix of both), with up to 20 links for each kinematics group.
- (2) In the Data Transfer Mode, the environment provides tools for setting up communication parameters and managing all communication with the Communication Proxy Module (CPM). The toolset provided consists of:
  - (a) Tools for setting up communication parameters, which identify the host and additional data/information necessary for establishing connection with the CPM.

- (b) Tools for managing communication with the CPM, which include tools for:
  - (1) starting/closing connection, (2) requesting data/information and (3) managing communication errors.
- (c) Tools for managing communication with one or more local project databases.
- (3) In the Simulation/Animation and Analysis Mode, the environment provides tools for performing simulation/animation and data analysis. The toolset consists of the following:
  - (a) Tools for performing simulation/animation using the loaded 3D virtual models. Two animation modes are provided: Jog Mode and Replay/Animation Mode. In the Jog Mode, tools for performing animation on each selected kinematics group and link are provided. In the Replay/Animation Mode, tools for performing animation/simulation, using data/information either stored in databases, or that provided by a simulation tool, are provided.
  - (b) A set of basic data analysis/processing/transformation tools is also provided. For demonstration purposes, the following tools are provided: (1) a transformation tool for obtaining frequency domain data from time domain data (e.g. used for Spectrum Analysis etc), (2) a transformation tool for obtaining 1<sup>st</sup> derivative from time domain data (e.g. used for deriving velocity datasets from displacement datasets etc), (3) a transformation tool for obtaining 2<sup>nd</sup> derivative from time domain data (e.g. used for deriving acceleration datasets from displacement datasets etc), (4) basic statistics tools for calculating statistics parameters such as standard deviation, variant etc.
  - (c) Typical navigation tools (typical to most CAD systems) for navigating the 3D virtual environment are provided, consisting of following: (1) zoom (windows zoom, dynamic zoom and 'all' zoom), (2) dynamic pan, (3) dynamic 3-dimensional rotation, (2) orthographic viewing in six typical directions and (3) isometric viewing in four typical directions.

#### **6.3.4.3 Communication Proxy Module**

The Communication Proxy Module (CPM) consists of three main components, as depicted in figure 6.10: (1) a Communication Manager Module, (2) an ASP.NET-based

Remote Communication Module and (3) a Winsock-based (TCP/IP) Local Communication Module. The Communication Manager Module is responsible for managing and coordinating the activities of the communication modules. The Remote Communication Module is responsible for communication with the Data/Information and Re-configuration Support Server Module (DIReSSM) while the Local Communication Module is responsible for communication with the Integrated 2D/3D Visualisation and Analysis Module (IVAM) and the local database. The Communication Proxy Module (CPM) communicates with the DIReSSM via two main communication protocols: (1) the Simple Object Access Protocol (SOAP) for communication with the XML Web Service Server of the DIReSSM (for service requests and short message exchanges such as alarm messages) and (2) the File Transfer Protocol (FTP) for communication with the FTP Server of the DIReSSM (for the transfer of data/software components) (See sub-section 6.3.4.6 for details of the DIReSSM.). The future version would include Microsoft's .NET Remoting for communication on a private network with the DIReSSM. For communication with the IVAM, the Local Communication Module makes direct use of the TCP/IP protocols (using the Winsock component). This allows it to run on any PCs on a local area network. For local database access, it uses the ActiveX Data Objects for .NET (ADO.NET).

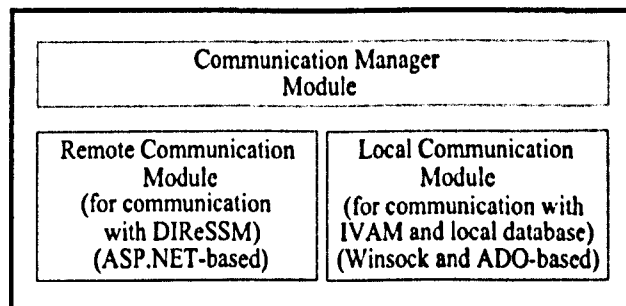


Fig. 6.10 Main components of the Communication Proxy Module

Figure 6.11 shows a screen shot of the main user interface of the CPM. With reference to the figure, the remote settings section and FTP communication settings section allow users to configure parameters such as the URLs for the XML Web Service Server and FTP Server etc. The local settings section allows users to configure

parameters such as the communication port (the Winsock port), details relevant to the local database etc. The current version has not included security-related configuration tools, which would be included in the future version.

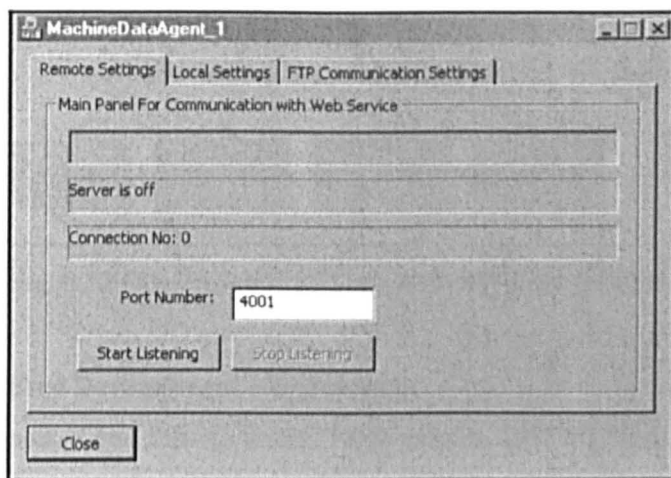


Fig. 6.11 User interface of the Communication Proxy Module

#### 6.3.4.4 Support Tools Library Server.

The Support Tools Library Server (STLS) provides data analysis support tools for the IVAM. Figure 6.12 depicts a simplified view of the configuration of the STLS. The support tools are based mainly on the data analysis components provided in the digital signal processing (DSP) toolboxes of MATLAB (MathWorks, 2004a) and LabVIEW (National Instruments, 2004). The STLS provides access to the support tools via the TCP/IP protocols (using the Winsock component), allowing it to serve the IVAM from any PCs on a local area network. It would also be possible to run multiple STLSs on multiple PCs on a local area network, each of which serves a different set of support tools. Additional support tool modules can be added to the library in the form of dynamic link libraries (DLLs) or MATLAB M-files (which require MATLAB to run). Current version requires the (minimum) re-compilation of the STLS for addition of new support tool modules. Future version would allow 'dynamic' addition (i.e. without requiring the re-compilation of the STLS) of new support tool modules.

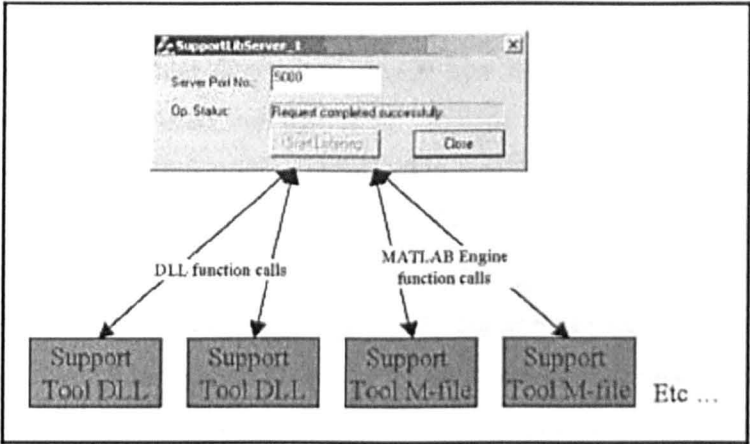


Fig. 6.12 Configuration of Support Tools Library Server

6.3.4.5 Support Tool Development Environment

The Support Tool Development Environment (STDE) consists of a set of commercial data manipulation/analysis and software development packages, namely MATLAB Version 7.0, LabVIEW Version 7.0 and Visual Studio Version 6.0. To allow sharing of data between the IVAM and the various packages, two forms of mechanisms are provided: (1) a Winsock-based (TCP/IP) interface coupled with the MATLAB Engine to facilitate data sharing with MATLAB workspace and (2) a Winsock-based (TCP/IP) interface coupled with a data exporter (to an ASCII text file) to facilitate data sharing with software modules developed using LabVIEW and Visual Studio (it can also be used by MATLAB). The developed support tools are packaged into either DLLs or MATLAB M-files. It would also be possible to compile MATLAB M-files into the DLL format (which requires a MATLAB compiler). Note that this environment could also be used for other purposes such as for the assessment of equipment’s design and refinement of simulation tools/models, analysis tools etc.

6.3.4.6 Re-configuration/Upgrade/Expansion Support Environment

For this study, the developed Re-configuration/Upgrade/Expansion Support Environment (RUESE) consists of only a rudimentary set of tools to demonstrate the basic concepts of the proposed strategy. For simplicity, it makes use of a commercial CAD tool – AutoCAD Version 2002 (Autodesk, 2005) for supporting the virtual re-



configuration/upgrade/expansion of equipment hardware (i.e. it allows changes to be made to the 3D CAD model in order to satisfy new functional requirements). Visual Studio Version 6.0 is used as the main control system software development environment. It also makes use of MATLAB environment for creating simulation models. The IVAM is used as the main visualization environment for supporting the development/re-configuration/upgrade/expansion and validation of the control system software components. Winsock-based (TCP/IP) communication is used to allow the developed/re-configured/upgraded/expanded control system software components to communicate its simulated output to the IVAM. It would also be possible to make use of various Hardware-in-the-loop (HIL) techniques (Delmia, 2005b; MathWorks, 2005b; Medeiros, et al., 1998; Raman, et al., 1999; Wu, et al., 2004) with the IVAM.

#### **6.3.4.7 Data/Information and Re-configuration Support Server Module**

The Data/Information and Re-configuration Support Server Module (DIRESSM) consists of two server types:

- (1) A SOAP-based XML Web Service Server, which is responsible for serving clients' requests for services.
- (2) An FTP Server, which provides services related to the transfer (either upload or download) of data/software components.

The future version would include a Microsoft's .NET Remoting-based server for communication, on a private network, with the CPM. For communication with the Automated Maintenance and Re-configuration Support Module (AMaReSM, see subsection 6.3.2.8 for details.), it uses the Winsock (TCP/IP) component. The current version has been designed to work with two major Database Management Systems (or database software): Microsoft SQL Server 2000 and Microsoft Access 2000.

#### **6.3.4.8 Automated Maintenance and Re-configuration Support Module**

The Automated Maintenance and Re-configuration Support Module (AMaReSM) consists of only a minimal set of modules for demonstrating the main concepts of the proposed Automated Maintenance and Re-configuration Support System (AMaReSS,

described in sub-section 5.3.6, chapter 5). The AMaReSM consists of the following components, as shown in figure 6.13:

- (1) A Main Coordinator Module (MCM, in the form of a Win32 application), acting as the main coordinator, responsible for coordinating the Re-configuration Support Module (ReSuM) and the Maintenance Support Coordinator Module (MaSCoM).

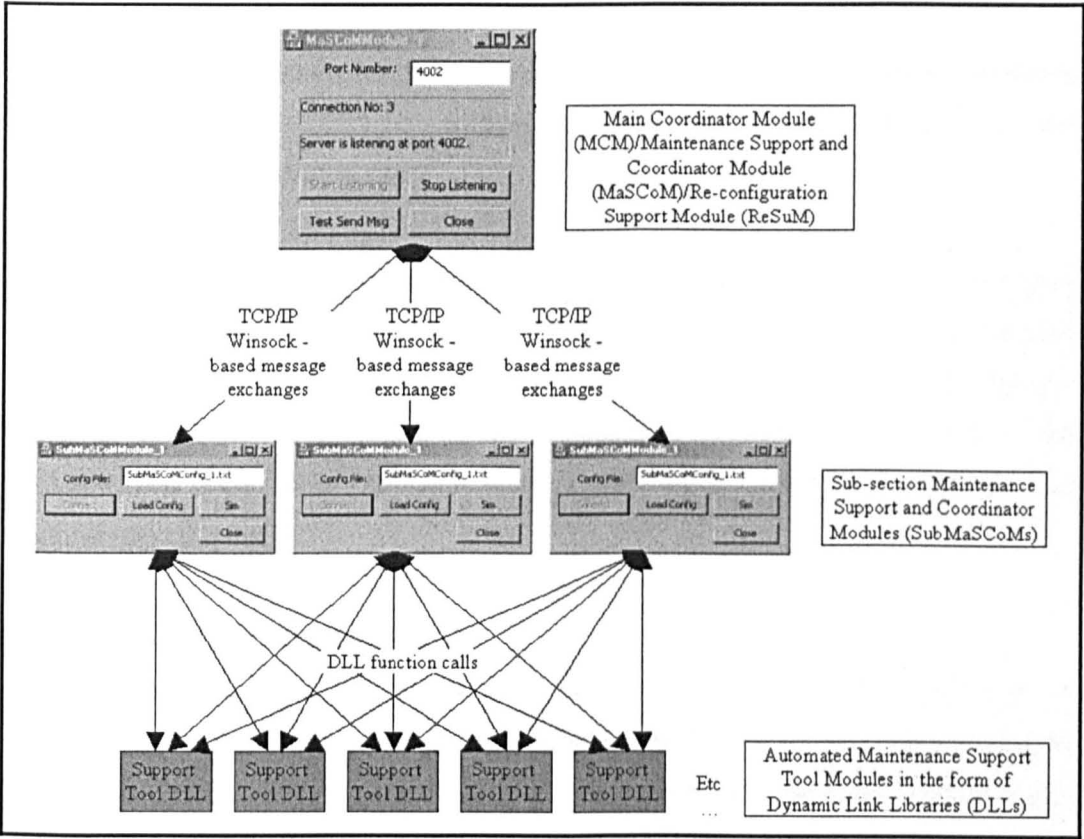


Fig. 6.13 Configuration of the Automated Maintenance and Re-configuration Support Module

- (2) A Re-configuration Support Module (ReSuM, in the form of a Win32 application), responsible for supporting the re-configuration operations for both the control system and automated maintenance support tools.

- (3) A Maintenance Support Coordinator Module (MaSCoM, in the form of a Win32 application), responsible for coordinating Sub-section Maintenance Support Coordinator Modules.
- (4) Three Sub-section Maintenance Support Coordinator Modules (Sub-MaSCoMs, in the form of a Win32 application), each of which is responsible for monitoring the selected operational parameters for each of the three axes of the SCARA robot. For simplicity, they perform only simple threshold checks on the selected parameters.
- (5) A set of maintenance support modules (in the form of Windows Dynamic Linked Library (DLL)), providing the necessary functions required for the purposes described in (4).

Note that for simplicity, the MCM, ReSuM and MaSCoM were combined into a single module (as a Win32 application). As shown in figure 6.13, for communication with the SubMaSCoMs, the combined MCM, ReSuM and MaSCoM module uses the Winsock (TCP/IP) component. For performing monitoring operations, the SubMaSCoMs issues DLL function calls to appropriate maintenance support tool modules (the DLL files).

#### **6.3.4.9 Machine Data Logger Module**

The Machine Data Logger Module (MDLM) is a simple Win32 application. It communicates directly with a PC-based controller (the NextMove PC-based Controller from Baldor Electric (Baldor Electric, 2005)) for acquiring data from the controller's data registers. For communication with the SubMaSCoMs, it uses TCP/IP message exchanges, based on the Winsock (TCP/IP) component.

## 6.4 Chapter Summary

This chapter has presented a description of the design and implementation of a prototype for demonstrating the main concepts of the proposed 3D-based Advanced Machine Service Support System/Strategy. The prototype was designed and developed based on the proposed reference architecture, described in chapter 5. It consists of a set of integrated modular network-ready software tools, consisting of: (1) an integrated 2D/3D visualisation and analysis module, (2) a set of support tools library modules, (3) communication modules and (4) a set of modular and re-configurable automated data logging, maintenance and re-configuration support modules. It has also presented a brief description of a test bed, at the Mechatronics Centre, De Montfort University, United Kingdom, used for this study. This research makes use of mainly a SCARA robot and a flexible conveyor system for demonstration and evaluation purposes. The next chapter (chapter 7) presents a description of the testing and evaluation aspects of this study, using the developed prototype.

## **Chapter 7**

### **Testing and Exploration**

#### **7.1 Introduction**

In this chapter, five test cases are presented. The test cases were conducted to demonstrate and explore the feasibility (technical) and effectiveness of the proposed 3D-based Advanced Service Support System/Strategy, based on the various scenarios described in section 4.4 of chapter 4 and section 5.4 of chapter 5. Section 7.2 to 7.6 present details of the test cases. Section 7.7 presents a summary of this chapter.

#### **7.2 Test Case 1**

##### **7.2.1 Introduction**

This test case was conducted to demonstrate and explore, based on scenario 1, i.e. for providing diagnostics/prognostics support in case of unplanned/unexpected equipment operation deviations/faults/failures (as described in sub-section 4.4.2 of chapter 4 and sub-section 5.4.2 of chapter 5), the feasibility and effectiveness of the proposed 3D-based Advanced Machine Service Support System/Strategy, more specifically:

- (1) To demonstrate how the proposed 3D-based Advanced Machine Service Support System integrates a 3D-based virtual environment with automated maintenance-support-tools in a network/Internet framework. The focus is demonstrating how a 3D-based visualization environment can be used to visualize the outputs of automated maintenance-support-tools, allowing the sources of equipment failures/operational deviations to be identified.
- (2) To demonstrate how the proposed 3D-based Advanced Machine Service Support System can be used to support remote experts (humans) in performing diagnostics/prognostics in cases where reliable automated maintenance-support-tools are unavailable.
- (3) To explore the feasibility and effectiveness of the proposed service support system/strategy for supporting remote experts (humans) in performing the maintenance support functions described in (1) and (2) above.

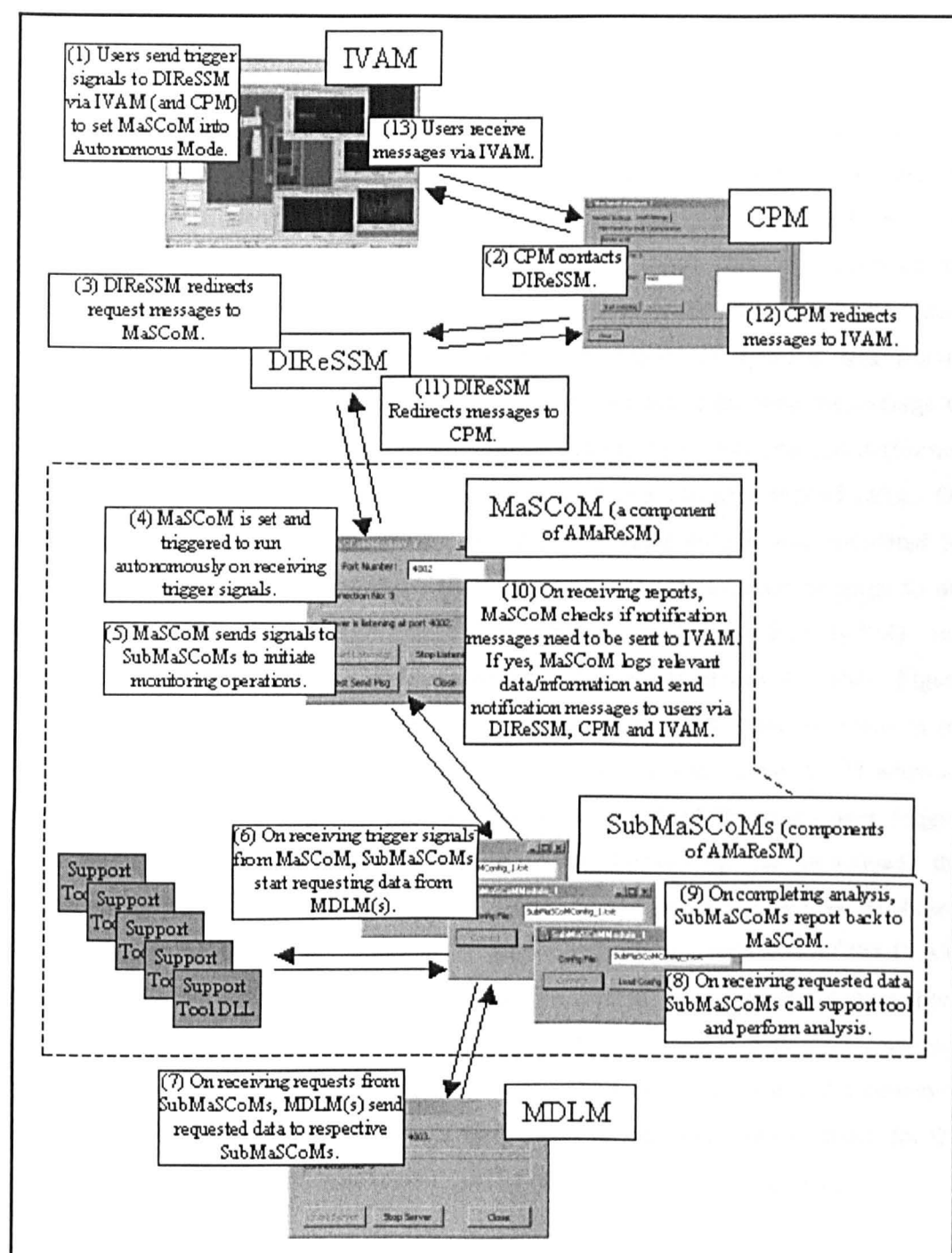


Fig. 7.1 Test Case 1: Typical event sequence in the Autonomous Mode

### 7.2.2 Test Procedures

In this test case, the Automated Maintenance and Re-configuration Support Module (AMaReSM) was set to run autonomously. The Maintenance Support Coordinator Module (MaSCoM) was configured to perform data analysis periodically. In each data analysis cycle, the MaSCoM communicated with the SubMaSCoMs, each of which was responsible for analysing data associated with one of the axes of the SCARA robot. For simplicity, the SubMaSCoM only performed simple threshold check on the vibration level of the velocity of each axis based on acquired raw data. The actual analysis was performed by a maintenance support module (a dynamic link library (DLL)). For demonstration, the maintenance support module calculated the average of actual velocity deviation (based on the average of velocity) for each axis and performed threshold check on the calculated deviation based on a user pre-set threshold value. On detecting vibration level beyond the pre-set threshold value (which was simulated by modifying the raw data), the corresponding SubMaSCoM sent an alert message to the MaSCoM, which then alerted the Communication Proxy Module (CPM) and subsequently, the Integrated 2D/3D Visualisation and Analysis Module (IVAM). Figure 7.1 illustrated a typical series of events, which take place when the support system is set to run in the Autonomous Mode. Figure 7.2 shows a screen shot of the IVAM when an alert is received. The IVAM was then used to download the associated logged data/information from the central database. On completing the download, the downloaded data/information could then be visualised and analysed using the 3D-based visualisation environment of the IVAM. Figure 7.3 shows a screen shot of the IVAM when it was used for the visualisation of the operational data/information of a more complex equipment system consisting of four SCARA robots and a flexible conveyor system. Note that the actual test bed consists of only a SCARA robot and a conveyor system. Three additional SCARA robots were added to the virtual environment, for the purpose of exploring the effectiveness of the IVAM for more complex systems.

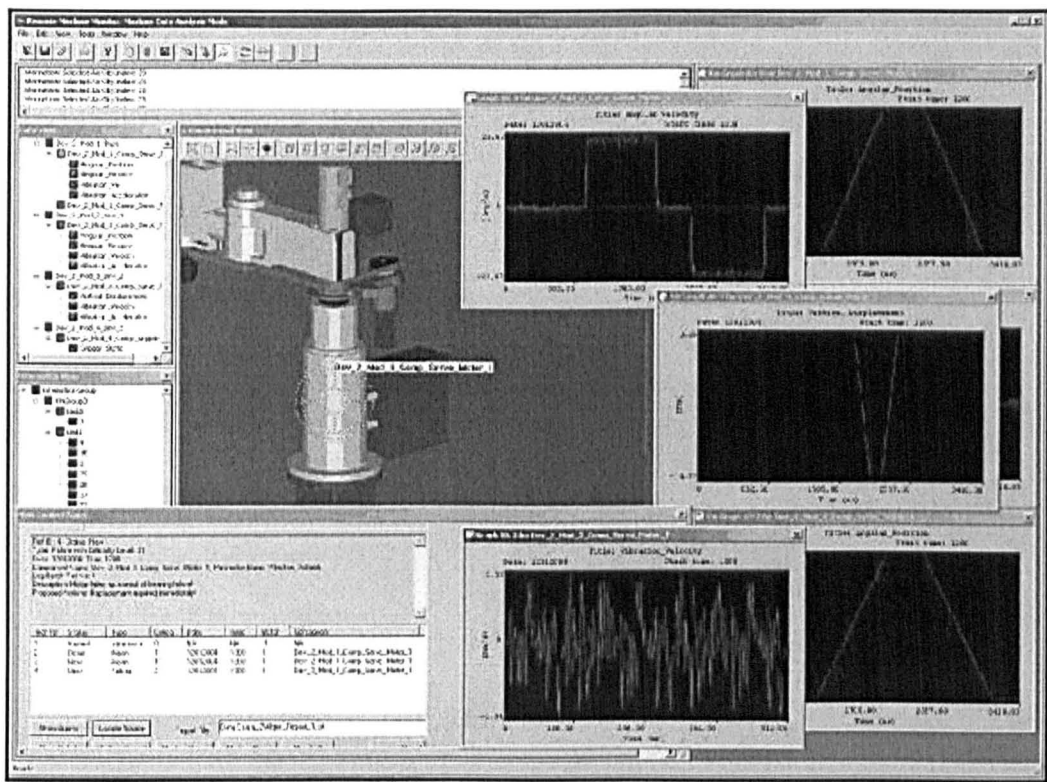


Fig. 7.2 Test Case 1: Visualisation of diagnostic outputs using the Integrated 2D/3D Visualisation and Analysis Module (for a SCARA robot)



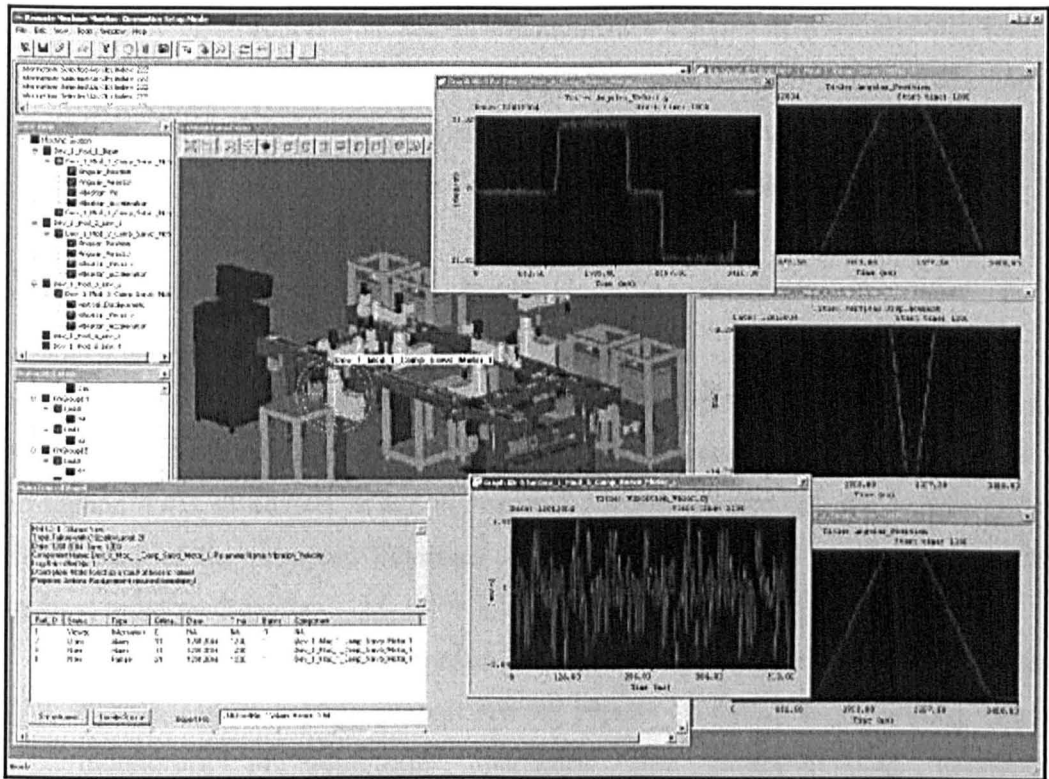


Fig. 7.3 Test Case 1: Visualisation of diagnostic outputs using the Integrated 2D/3D Visualisation and Analysis Module (for a more complex system)

### 7.2.3 Discussion

The demonstration has shown:

- (1) The potential of implementing the proposed service support system/strategy for the purposes described in scenario 1. However, due to the limited scale of the test bed, further experimentation based on larger-scale industrial test beds is required to further assess the effectiveness of the proposed service support strategy.
- (2) By integrating a 3D-based virtual environment with automated maintenance-support-tools, it has the potential for improving the visualization of outputs of automated maintenance-support-tools, allowing the sources of equipment failures/operational deviations to be identified efficiently. This is particularly useful for cases involving complex systems.
- (3) A 3D-based virtual environment when being used as proposed in the Integrated 2D/3D Visualisation and Analysis Environment (IVAE) has the potential for

improving current remote machine maintenance support strategy, allowing remote machine experts to more efficiently and effectively visualize and analyse complex sets of equipment data/information (for diagnostics/prognostics) in cases where reliable automated maintenance-support-tools are unavailable.

## **7.3 Test Case 2**

### **7.3.1 Introduction**

This test case was conducted to demonstrate and explore, based on scenario 2, i.e. for providing remote condition-based preventive maintenance support (as described in sub-section 4.4.3 of chapter 4 and sub-section 5.4.3 of chapter 5), the feasibility and effectiveness of the proposed 3D-based Advanced Machine Service Support System/Strategy, more specifically:

- (1) To demonstrate how the proposed 3D-based Advanced Machine Service Support System can be used to support remote experts (humans) in performing remote monitoring of equipment operations (for condition-based preventive maintenance).
- (2) To explore the feasibility and effectiveness of the proposed service support system/strategy for supporting remote experts (humans) in performing the maintenance support functions described in (1) above.

### **7.3.2 Test Procedures**

In this test case, a request for initiating a data acquisition session was issued via the Integrated 2D/3D Visualisation and Analysis Module (IVAM). The IVAM then communicated with the Communication Proxy Module (CPM) and passed on all relevant details associated with the request. Next, the CPM sent a request to the XML Web Service Server of the Data/Information and Re-configuration Support Server Module (DIRESSM). On receiving the request, the DIRESSM redirected the request message to the Automated Maintenance and Re-configuration Support Module (AMaReSM). The MaSCoM of the AMaReSM communicated directly with the Machine Data Logger Module (MDLM) as the request was for raw data. The MDLM first logged the requested data into a temporary buffer. The MaSCoM then transferred the logged data from the

buffer into the central database (the Database 1 of figure 6.7). On completing the data transfer, the DIReSSM issued a 'data ready' notification to the Integrated 2D/3D Visualisation and Analysis Module (IVAM) via the Communication Proxy Module (CPM). Next, the user issued command via the IVAM to the Data/Information and Re-configuration Support Server Module (DIReSSM) for downloading the logged data from the central database (the Database 1 of figure 6.7) to the local database (the Database 2 of figure 6.7). Once the download was completed, the downloaded data/information was visualised using the IVAM.

A similar step was repeated with a request for initiating an automated data analysis session. The sequence of events taking place in this case is similar to that described in test case 1. The main difference is that in this case, the (Maintenance Support and Coordinator Module) MaSCoM was set to perform monitoring operation only once and report all analysis results to users. Figure 7.4 shows a screen shot of the IVAM when it was used for visualisation of archived historical operational data of the SCARA robot such as angular position, velocity, vibration data etc. Figure 7.5 shows a screen shot of the IVAM when it was used for the visualisation of operational data/information of a more complex system.

### **7.3.3 Discussion**

The demonstration has shown:

- (1) The potential of implementing the proposed service support system/strategy for the purposes described in scenario 2. Similar to test case 1, due to the limited scale of the test bed, further experimentation based on larger-scale industrial test beds is required to further assess the effectiveness of the proposed service support strategy.

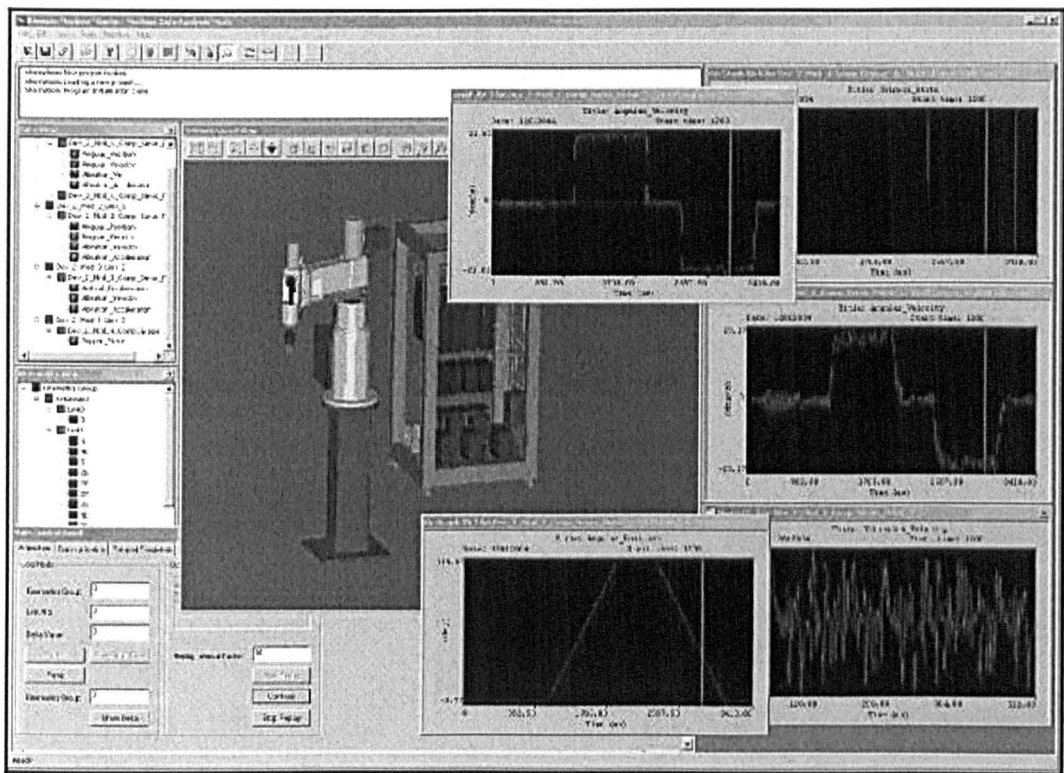


Fig. 7.4 Test Case 2: Data/information visualisation and analysis using the Integrated 2D/3D Visualisation and Analysis Module (for a SCARA robot)

(2) A 3D-based virtual environment when being used as proposed in the Integrated 2D/3D Visualisation and Analysis Environment (IVAE) has the potential for more effectively supporting machine experts (humans) in performing continuous remote monitoring of equipment operations. The IVAM has demonstrated that a 3D-based virtual environment could facilitate data access and visualization, relieving machine experts of lower level data/information management tasks. This allows machine experts to focus on tasks in hand. This is especially evident in cases involving complex systems, which typically consists of a large number of components.

It has also been found that:

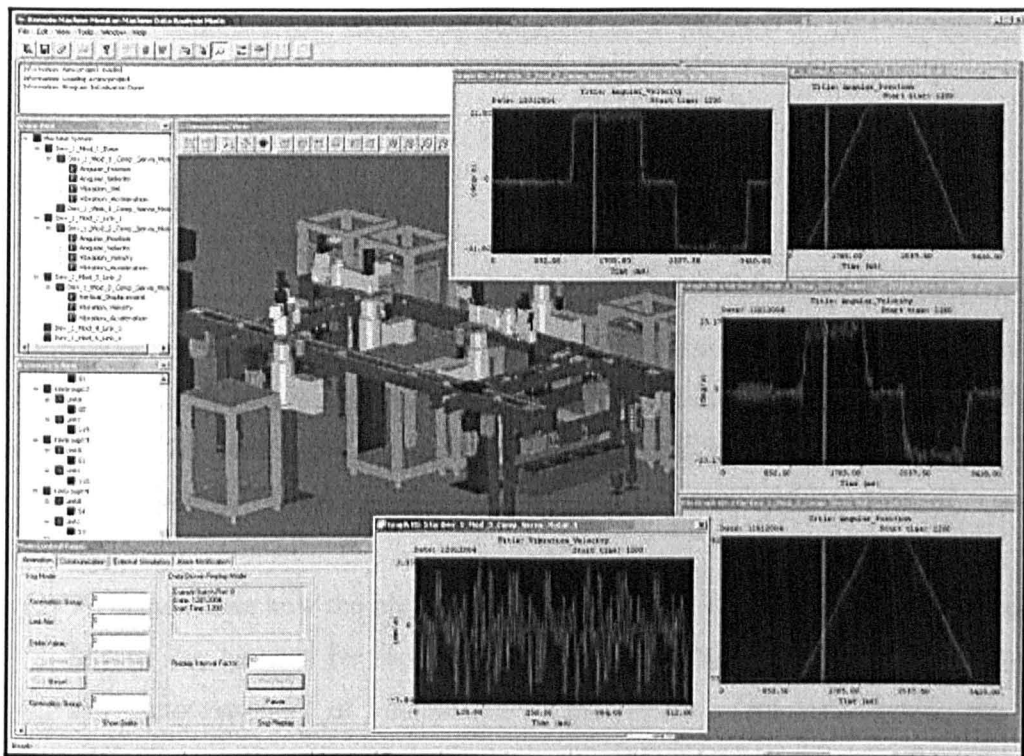


Fig. 7.5 Test Case 2: Data/information visualisation and analysis using the Integrated 2D/3D Visualisation and Analysis Module (for a more complex system)

(3) For cases involving complex systems, the current design of the IVAM may be insufficient as it is based only on a single monitor (PC monitor). For such cases, the following possible improvements have been identified:

- (a) Using enlarged screen such as with a projector.
- (b) Distributing the visualization windows across multiple PCs, i.e. separating the IVAM into smaller modules, each of which is responsible for the visualization of a particular aspect of a complex system
- (c) Running multiple IVAM modules on multiple PCs with each of the modules being responsible for the visualization of a section of a complex system.
- (d) Structuring the 3D geometric model into different levels of details. More detailed sub-models are retrieved only when necessary, which could be visualized either via a visualization window or a number of separate

windows (on either the same PC or a number of PCs on the same network).

## **7.4 Test Case 3**

### **7.4.1 Introduction**

This test case was conducted to demonstrate and explore, based on scenario 3, i.e. for providing support for the implementation of maintenance-support-tools, in particular the automated/intelligent maintenance-support-tools (as described in sub-section 4.4.4 of chapter 4 and sub-section 5.4.4 of chapter 5), the feasibility and effectiveness of the proposed 3D-based Advanced Machine Service Support System/Strategy, more specifically:

- (1) To demonstrate how the proposed 3D-based Advanced Machine Service Support System can be used for supporting the in-service implementation, development and improvement of maintenance-support-tools (automated/intelligent or partially-automated).
- (2) To explore the feasibility and effectiveness of the proposed service support system/strategy for supporting remote experts (humans) in performing the maintenance support functions described in (1) above.

### **7.4.2 Test Procedures**

In this test case, the Integrated 2D/3D Visualisation and Analysis Module (IVAM) was used to visualise archived historical data/information for supporting the development of new maintenance-support-tools. MATLAB was used as the main analysis and development environment for new maintenance-support-tools. The IVAM was integrated with MATLAB via the Data Export Module of the IVAM, allowing archived historical data to be exported to MATLAB workspace. Within MATLAB workspace, the imported data was further analysed/visualised (a screenshot is shown in figure 7.8). A simple Fast Fourier Transform-based (FFT-based) maintenance-support-module was created using MATLAB's built-in FFT function. The module was 'packaged' into a MATLAB's M-file. A module performing similar function was also developed using LabVIEW. It was compiled into a DLL. The modules were then added

to the Support Tools Library (STL). Once added to the STL, the functions provided by the modules could be called from within the IVAM (via the Support Tools Library Server (STLS)). Figure 7.7 shows a screen shot of the output of the FFT analysis module.

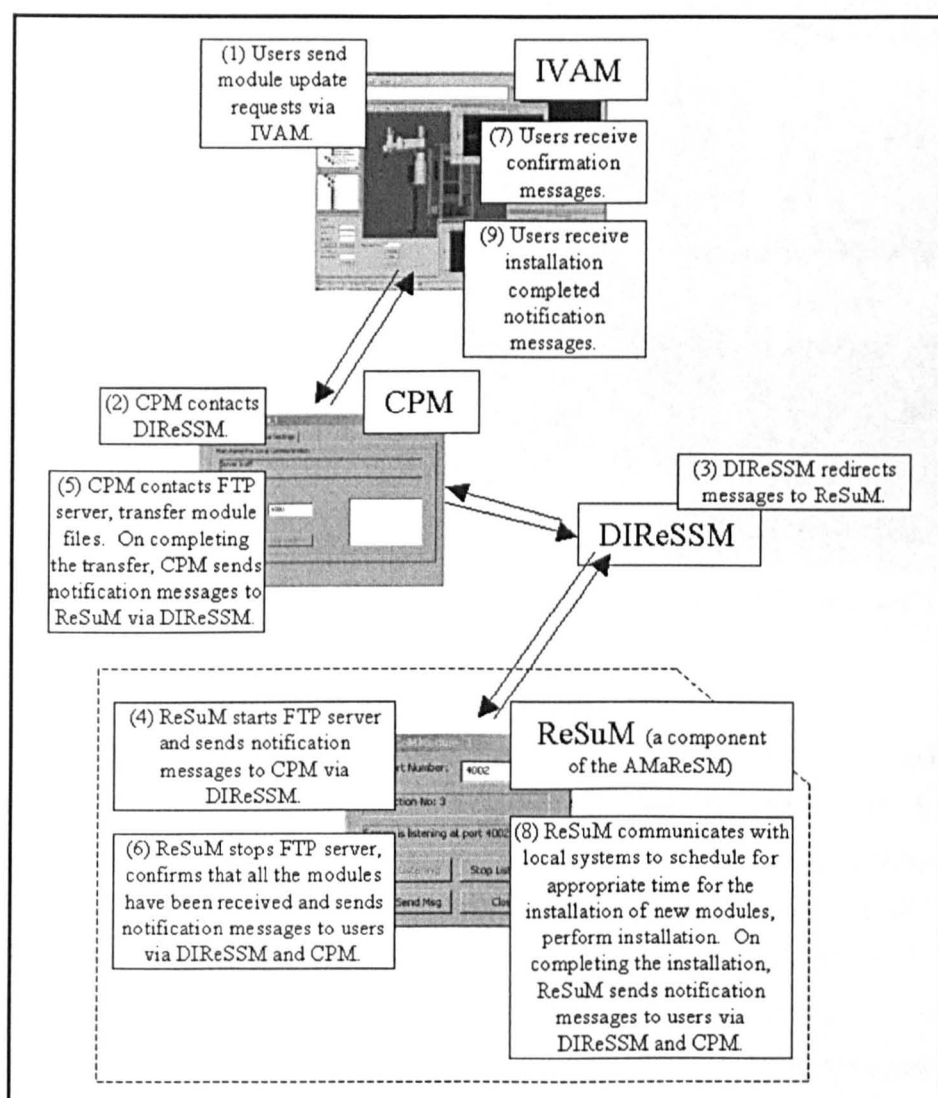


Fig. 7.6 Test Case 3: Typical remote module installation process

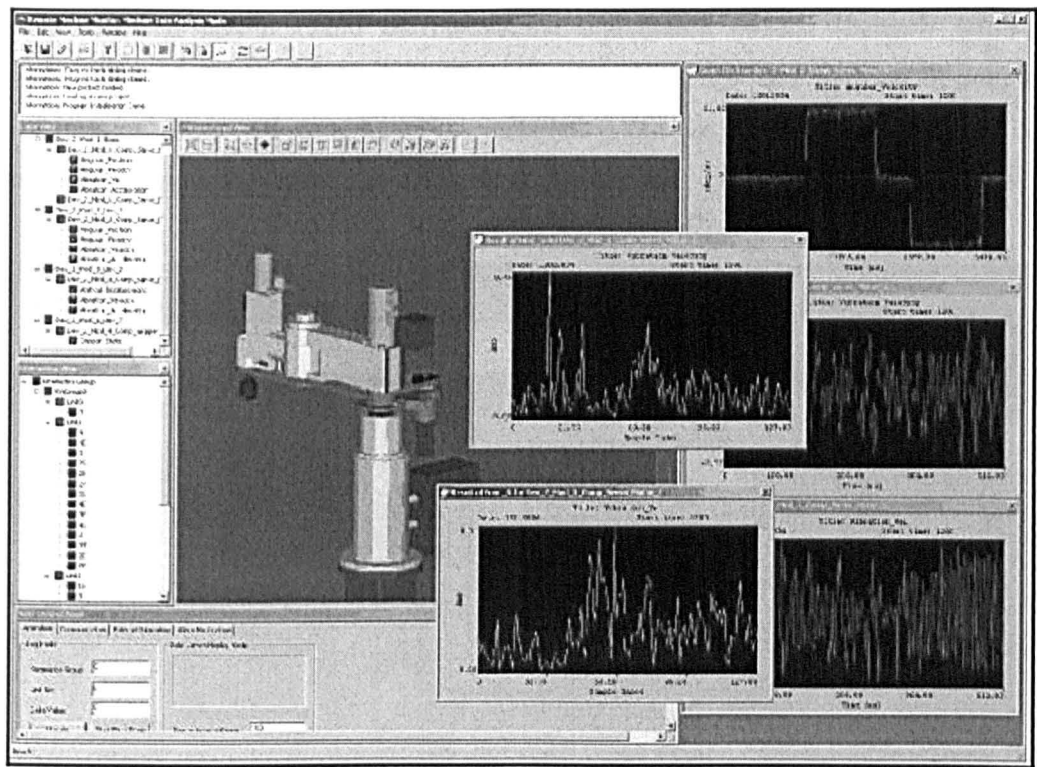


Fig. 7.7 Test Case 3: Calling an FFT analysis module from within the Integrated 2D/3D Visualisation and Analysis Module

The DLL version of the module was also installed into the Automated Maintenance and Re-configuration Support Module (AMaReSM). Figure 6.20 illustrates a typical remote module installation process. For performing installation, a request was first sent to the Re-configuration Support Module (ReSuM, a component of the Automated Maintenance and Re-configuration Support Module (AMaReSM)) via the Data/Information and Re-configuration Support Server Module (DIRESSM) and the Communication Proxy Module (CPM). On receiving the request, the ReSuM started the FTP Server and notified the CPM via the DIRESSM. Subsequently, the CPM started transferring (uploading) all the relevant module files to the FTP Server. On completing the transfer, the CPM notified the ReSuM via the DIRESSM. Next, the ReSuM performed checks on all received files and sent a confirmation message to the user via the DIRESSM, CPM and IVAM, and stopped the FTP Server. The ReSuM then communicated with MaSCoM to schedule an appropriate time for the installation of the



newly received modules and performed the installation (which basically involved copying the received module files to appropriate locations and updated appropriate configuration files). On completing the installation process, a notification message was sent to the user via the DIReSSM, CPM and IVAM.

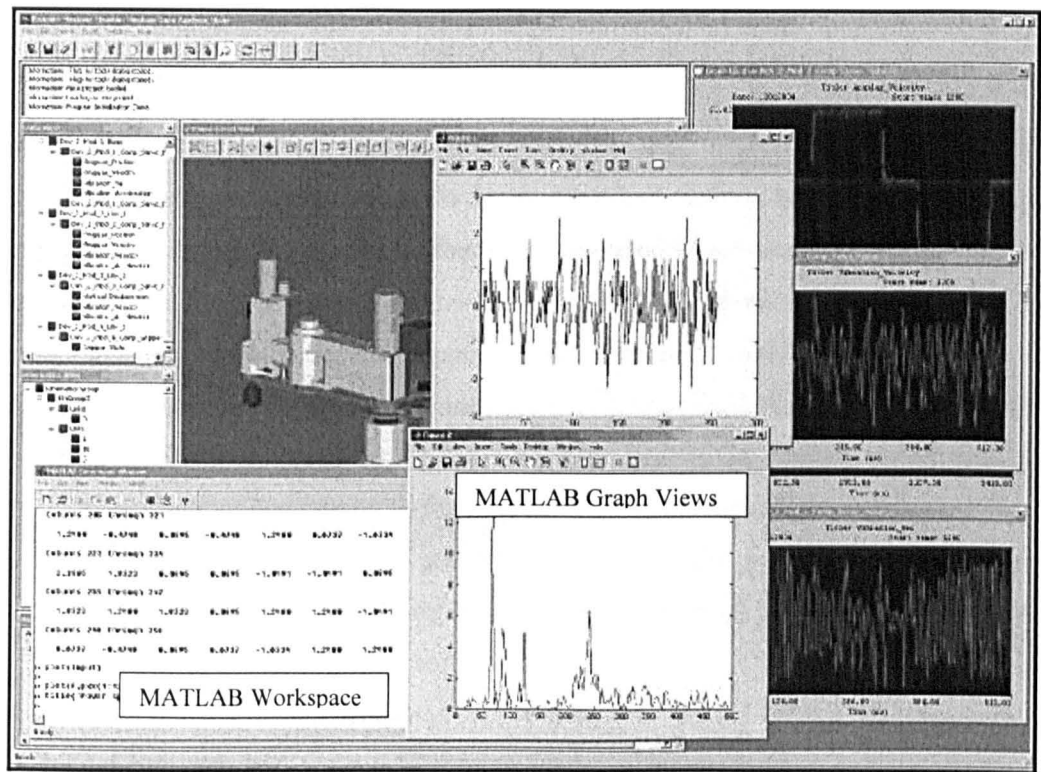


Fig. 7.8 Test Case 3: Data sharing between the Integrated 2D/3D Visualisation and Analysis Module and MATLAB

7.4.3 Discussion

The demonstration has shown:

(1) The potential of implementing the proposed service support system/strategy for the purposes described in scenario 3. The prototype has demonstrated various possibilities of how a 3D-based virtual environment could be integrated with various commercial data analysis and software development tools (e.g. MATLAB, LabVIEW, Microsoft Visual Studio etc) for supporting the continuous development and improvement of maintenance-support-tools. It has been

demonstrated that a 3D-based virtual environment could provide machine experts (humans) with an intuitive environment allowing them to efficiently access and re-use available data/information and tools. It is particularly useful for cases involving complex systems, which typically consists of a large number of components.

## **7.5 Test Case 4**

### **7.5.1 Introduction**

This test case was conducted to demonstrate and explore, based on scenario 4, i.e. for facilitating equipment design feedback (as described in sub-section 4.4.5 of chapter 4 and sub-section 5.4.5 of chapter 5), the feasibility and effectiveness of the proposed 3D-based Advanced Machine Service Support System/Strategy, more specifically:

- (1) To demonstrate how the proposed 3D-based Advanced Machine Service Support System can be used to support machine experts in remote monitoring and assessment of equipment performance (for design feedback purposes).
- (2) To explore the feasibility and effectiveness of the proposed service support system/strategy for supporting remote experts (humans) in performing the service support functions described in (1) above.

### **7.5.2 Test Procedures**

In this test case, the Integrated 2D/3D Visualisation and Analysis Module (IVAM) was used as a design feedback tool. It provides an intuitive environment allowing the performance of equipment to be visualised, analysed and assessed efficiently, output of which could be used for optimising equipment' performance. In the demonstration, a set of acquired equipment operational data was first analysed within the IVAM using tools provided by the Support Tools Library Server (STLS). Then, the same dataset was exported to the MATLAB workspace allowing further analysis to be performed. Similar to that described in test case 3, data was exported to the MATLAB workspace via the Data Export Module, allowing archived historical data to be shared efficiently with the MATLAB environment. In addition to equipment performance analysis, there are various other support activities, which can be performed using the

integrated environment, such as: (1) identification of design flaws/design deficiencies (particularly if the flaws/deficiencies were linked with particular recurring equipment malfunctions), note that via the environment, users can also access archived historical operational data/information associated with past failure events etc, (2) identification of opportunities for the improvement and optimisation of design support tools such as simulation tools/models etc, the improved tools can then be packaged into a form accessible from within the IVAM for future use.

### **7.5.3 Discussion**

The demonstration has shown:

- (3) The potential of implementing the proposed service support system/strategy for the purposes described in scenario 4. The prototype has demonstrated how a 3D-based virtual environment can be integrated with commercial data manipulation/analysis tools (e.g. MATLAB etc).
- (4) A 3D-based virtual environment has the potential of being used to create an effective platform for providing a systematic and efficient design feedback mechanism allowing equipment to be supported more effectively. This would allow equipment to be continuously improved and optimized during its in-service life. In addition, it could also bring in benefits to other activities such as re-configuration/upgrade/expansion support (See test case 5 described in sub-section 7.6 for details.) and future design activities via development/improvement and refinement of design support tools such as simulation tools etc.

## **7.6 Test Case 5**

### **7.6.1 Introduction**

This test case was conducted to demonstrate and explore, based on scenario 5, i.e. for providing extended service support (equipment re-configuration/upgrade/expansion support) (as described in sub-section 4.4.6 of chapter 4 and sub-section 5.4.6 of chapter 5), the feasibility and effectiveness of the proposed 3D-based Advanced Machine Service Support System/Strategy, more specifically:

- (1) To demonstrate how the proposed 3D-based Advanced Machine Service Support System can be used to support remote experts (humans) in providing extended service support for equipment in the form of re-configuration/upgrade/expansion support.
- (2) To explore the feasibility and effectiveness of the proposed service support system/strategy for supporting remote experts (humans) in performing the service support functions described in (1) above.

### 7.6.2 Test Procedures

In this test case, the Integrated 2D/3D Visualisation and Analysis Module (IVAM) was used to visualise the simulation output of an external simulator (which simulated a prototype PC-based control application (LabVIEW-based) for the SCARA robot), as illustrated in figure 7.9. For simplicity, the external simulator was based on a simplified inverse kinematics model of the SCARA robot. For communication with the IVAM, the external simulator used the TCP/IP Winsock component. During simulation, the IVAM continuously reads the simulation output of the external simulator and updated the 3D main view (and optionally, all associated graph views). For demonstrating the idea of 'virtual re-configuration', an external commercial CAD system – Autocad Version 2002 was used as the re-configuration environment. Ideally, the IVAM should provide functions to allow users to virtually re-configure the 3D Virtual Machine System in the main 3D view of the IVAM. However, the current version of the IVAM has not incorporated such functions, which would be added in the future version. The updated 3D Virtual Machine System was then re-loaded into the IVAM. Next, the environment was re-configured to accommodate changes made to the virtual machine system. After the re-configuration, the 're-configured' virtual machine system was used as reference to modify the external simulator and the prototype controller application. Next, by using the IVAM, simulations are re-run and the simulation output was visualised and analysed. The prototype controller application was then assessed, refined/debugged and validated (to some extent) using the 're-configured' virtual machine system. It should be noted that in the demonstration, as the external simulator is simplified, only the logic of the prototype control application could be validated (to some degree). This could be

improved by incorporating various available Hardware-in-the-loop (HIL) techniques into the prototype of the service support system. In addition, the simulation output could be archived for future reference, if necessary. The integrated environment also provides a platform, allowing users to access archived historical data/information and tools associated with previous equipment designs.

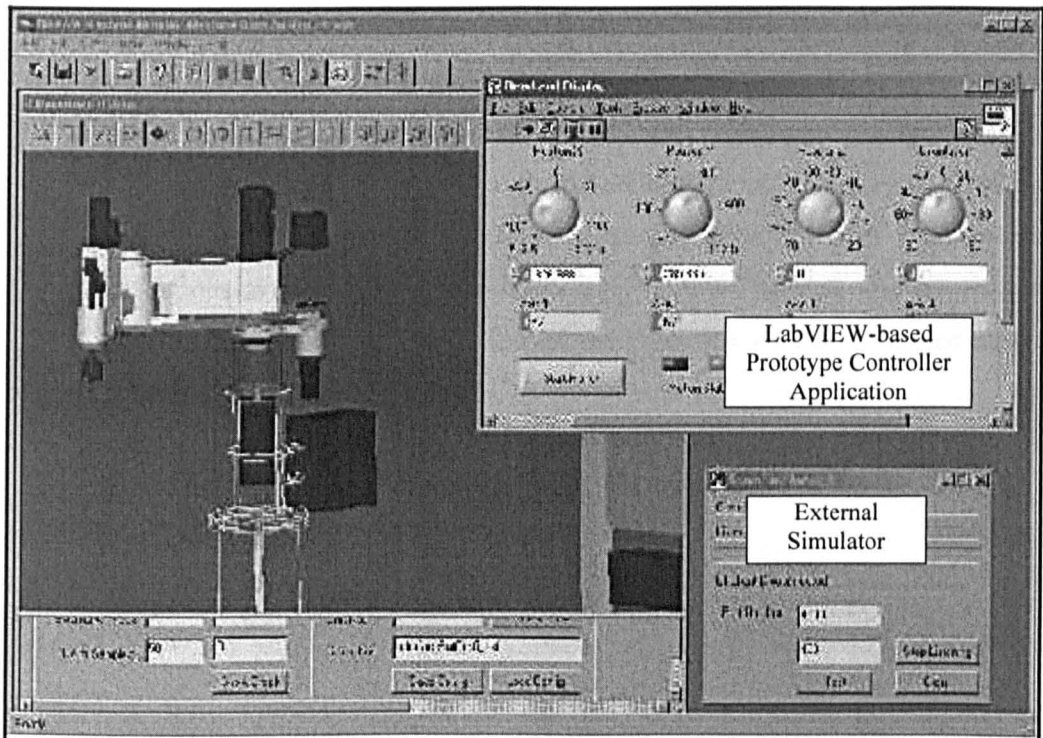


Fig. 7.9 Test Case 5: Integration of Integrated 2D/3D Visualisation and Analysis Module with an external simulator

### 7.6.3 Discussion

The demonstration has shown:

- (1) The potential of implementing the proposed service support system/strategy for the purposes described in scenario 5. It has been demonstrated that by using the prototype service support system, it is possible to develop and validate (to some extent, depending on the comprehensiveness and accuracy of available simulation models/emulation tools) a prototype machine controller application (software)

even before the real machine system is ready. This effectively allows the re-configuration/upgrade/expansion operations for the software and hardware of a manufacturing system to be performed in parallel. However, further experimentation based on larger-scale test beds and using various (Hardware-in-the-loop) HIL techniques is required to further assess the effectiveness of the proposed strategy/system.

- (2) A 3D-based virtual environment when being integrated in the way proposed, has the potential as an effective platform for allowing the proposed extended service support functions to be performed efficiently. One of the potential advantages of the proposed strategy is that it allows efficient sharing and re-use of archived past data/information (experience and knowledge) and support tools. This, coupled with various available (Hardware-in-the-loop) HIL techniques, has the potential for streamlining the implementation of the proposed extended service support functions.

## 7.7 Chapter Summary

This chapter has presented a description of five test cases, conducted for demonstrating, testing and exploring the feasibility (technical) and effectiveness of the proposed strategy/system. The outcomes have shown the potential of the proposed 3D-based approach as a strategy for improving existing machine service support strategies/systems for new generation manufacturing systems. In summary, it has the potential for allowing machine builders/suppliers:

- (1) To more efficiently and cost-effectively provide conventional maintenance support services (explored in test case 1 and 2).
- (2) To continuously and efficiently improve and extend the capabilities of automated maintenance-support-tools (explored in test case 3).
- (3) To continuously and efficiently improve and optimize the performance and design of remote equipment system (explored in test case 4).
- (5) To more cost-effectively provide extended service support services in the form of equipment re-configuration, upgrade and expansion (explored in test case 5).

However, due to the limited scale of the test bed (as it is based on a laboratory-scale test bed), further development and experimentation based on an industrial-scale test bed is required. The prototype has provided a foundation for such future research and development work. The next chapter (chapter 8) presents the summary, findings, contributions and conclusions of this research study. It also presents some issues/recommendations identified for future work.

## **Chapter 8**

# **Conclusions and Recommendations for Future Work**

### **8.1 Research Summary**

This research study has been undertaken to explore how 3D-based virtual environments can be used to create a virtual integration platform to support a more advanced strategy for improving service support for new generation manufacturing systems. Literature reviews have indicated the need for a more cost-effective and comprehensive strategy for new generation manufacturing systems, specifically in the following areas: (1) more streamlined remote maintenance support (which includes remote fault detection, diagnostics, prognostics and maintenance decision support) and (2) broader range of support services (which includes remote support for equipment re-configuration, upgrade and expansion). The lack of such an integrated service support strategy for new generation manufacturing systems, coupled with the unexplored potential of 3D virtual technology for supporting such a strategy, served as motivations for undertaking this research study.

In the initial phase of the study, extensive reviews of current developments in machine service support strategies were conducted, as presented in chapter 2 and 3. The review of literature indicated that significant advances have been made in various aspects/areas, particularly, in regard to the following: (1) remote/web-based maintenance support strategies/systems, (2) intelligent/automated Condition-based Maintenance techniques, (3) remote/web-based visualisation technologies (4) sensor and data acquisition technologies and (5) emergence of open architectures/standards. The review has also revealed several issues, which require further research, in respect of improving remote service support for new generation manufacturing systems. In general, the issues were: (1) the lack of a cost-effective and efficient mechanism for the remote implementation, assessment, improvement and re-configuration/upgrade support for intelligent/automated maintenance-support-tools, (2) the lack of a comprehensive and efficient mechanism for the continuous remote improvement and optimisation support for



complex new generation manufacturing systems, (3) limitations of existing approaches to the remote management and visualisation of a large quantity of multivariate and multi-level equipment data/information, (4) the lack of an efficient strategy the implementation of extended remote service support functions such as equipment re-configuration/upgrade/expansion support and (5) the lack of a strategy to seamlessly integrate the extended service support functions and the remote maintenance support functions into a more integrated remote machine service support strategy/system.

In the course of the study, (iterative) research into the potential of a 3D-based virtual environment as a virtual integration platform for machine service support activities was conducted. Initial experimentation conducted under an industry-based project (MASSIVE, as presented in chapter 3) has demonstrated the potential of a 3D-based approach to integrating machine maintenance support functions for improving remote monitoring and diagnostics. It provided a foundation and motivation for extending this research into further exploration of the potential of a 3D-based virtual environment for more advanced service support for new generation manufacturing systems. The main activities (which are essentially iterative in nature) of this research study can be summarised as follows: (1) identification of requirements for an advanced remote service support strategy/system, (2) formulation of conceptual frameworks for an improved remote service support strategy/system, (3) implementation of the formulated frameworks, which involves the development of a prototype based on a laboratory test bed, (4) testing, exploration, reflection and feedback, which provide inputs for the refinement of the initial reference frameworks. The final version of a conceptual framework for a proposed 3D-based advanced machine service support strategy/system has been presented in chapter 4 and 5. Experimentation using a prototype based on a laboratory-scale test bed, as presented in chapter 6, was conducted to explore the potential of the proposed approach. The outcomes have shown the potential benefits of the proposed approach.

## 8.2 Research Findings

- (1) Research Question 1: To what degree a 3D-based virtual environment is effective, as a virtual platform for the integration of extended service support functions (i.e. re-configuration/upgrade/expansion support) and maintenance support functions?**

It was found that a 3D-based virtual environment has the potential of providing an effective platform for integrating remote maintenance support and extended service support functions, for new generation manufacturing systems. By integrating the 3D-based virtual environment with other support tools/environments and data/information sources, it has the potential for allowing various service support activities to be performed in a more integrated and coordinated manner. The identified service support activities are: conventional maintenance support, automated maintenance support (which is performed by automated maintenance-support-tools, embedded in the machine system), maintenance-support-tool/strategy support, equipment design feedback support and extended service support activities. It was observed that the 3D-based approach facilitates the management, visualisation, sharing and re-use of complex sets of equipment data/information without requiring frequent site visits. This provides a common environment allowing the various machine service support activities to be coordinated in a more systematic manner.

- (2) Research Question 2: What are the challenges and limitations of the approach? What are the available opportunities for overcoming the challenges and limitations (if there is any)?**

From the technical perspective, it was found that in cases involving complex mechatronics systems:

- (a) 3D visualisation alone is insufficient. Accordingly, there is a need for a more comprehensive visualisation tool. In addition to the main 3D visualisation of the geometric aspects of an equipment system, it should also allow the visualisation of other non-geometric/non-mechanical aspects. To achieve this, the visualisation tool should take advantage of 2D visualisation techniques and remote/web-based video technologies

(which do not necessarily require real-time performance). From the implementation of a prototype system incorporating a 2D/3D visualisation module, it was observed that by integrating 3D-based visualisation tools with 2D-based/video-based tools, the visualisation capability could be improved significantly. It allows the various aspects of a mechatronics system (such as the mechanical, electrical/electronic, control and software aspects) to be visualised and correlated more efficiently (as described in chapter 6 and 7).

- (b) For cases involving complex manufacturing systems, with regard to the implementation of the proposed Integrated 2D/3D Visualisation and Analysis Environment (IVAE, see sub-section 5.3.3.2 for details), the visualisation capability of the IVAE may be improved in one of the following ways: (1) using enlarged screen such as with a projector, (2) distributing the visualization windows across multiple PCs, i.e. separating the IVAE into smaller modules, each of which is responsible for the visualization of a particular aspect of a complex system, (3) running multiple IVAE modules on multiple PCs with each of the modules being responsible for the visualization of a section of a complex system or, (4) structuring the 3D geometric model into different levels of details. More detailed sub-models are retrieved only when necessary, which could be visualized either via a visualization window or a number of separate windows (on either the same PC or a number of PCs on the same network).

A number of non-technical issues, which may affect the feasibility/effectiveness of the proposed approach, have been identified as follows:

- (a) As close collaboration between the machine user and the machine builder is a pre-requisite for the proposed approach to be feasible, it would not be practical for cases where the machine user is unwilling to allow the machine builder to have remote access to the equipment data. In such cases, the implementation of the strategy may need to be adjusted in one/both of the following ways: (1) the machine builder may need to

provide incentives such as some form of uptime guarantees, free onsite services (for a limited time period) etc and (2) the strategy may need to be implemented partially/incrementally and re-adjust in the future when the machine user has gained more confidence in the support strategy/system.

- (b) It is crucial for the reference data/information used by the machine builder to be updated whenever changes are made to the equipment being monitored. However, in practice, a number of factors may give rise to inconsistencies in the data/information used such as changes to equipment, which are not updated systematically, undetected failures/limitations of the data acquisition system, design deficiencies etc. In order to minimise the impact of the various issues, the following should be in place: (1) a support tool/system/strategy that facilitates the update process, (2) close co-operation and coordination with the machine user and (3) the data acquisition system (including sensors) should be designed in such a way that they can be monitored, serviced and upgraded efficiently.

- (3) Research Question 3, 4 and 5: How a 3D-based virtual environment can be used to integrate various existing maintenance support strategies/tools for streamlining current maintenance support for new generation manufacturing systems? How a 3D-based virtual environment can be used to support efficient extended service support functions for new generation manufacturing systems? How a 3D-based virtual environment can be used to seamlessly integrate extended service support functions and maintenance support functions?**

They have been demonstrated via a proposed 3D-based advanced machine service support strategy and a corresponding support system. A summary of the proposed service support strategy/system is given in section 8.3 – under the second contribution. Details have been presented in chapter 4, 5, 6 and 7.

### 8.3 Research Contributions

- (1) This research study has contributed a novel approach of using a 3D-based virtual environment as an integration platform for improving the capability of machine builders/suppliers in providing more cost-effective and comprehensive machine service support for new generation manufacturing systems. It has contributed to a number of key findings (See section 8.2 for details.). The outcomes of the study support the hypothesis that a 3D-based virtual environment can be used as an integration platform to improve service support for new generation manufacturing systems.
- (2) A conceptual framework for a novel 3D-based advanced remote service support strategy and a corresponding service support system for new generation manufacturing systems has been formulated. It suggests the implementation of a systematic and integrated strategy to support the machine builder/supplier in the shift from the conventional '**product-based business model**' to the more sustainable '**service-based business model**' (Takata, et al., 2004). This has resulted in a number of advances in remote machine support strategies as follows:
  - (a) Integration of remote support functions for supporting the development, testing, assessment and installation/re-configuration/upgrade of automated/intelligent maintenance-support-tools, to allow the maintenance-support-tools to be leveraged more cost-effectively.
  - (b) Integration of a remote design feedback and control system re-configuration support mechanism for facilitating continuous improvement and optimisation of new generation manufacturing systems during their in service life. The proposed mechanism is intended for facilitating not just equipment performance improvement and optimisation, but also providing an efficient mechanism for supporting long-term equipment design improvement and optimization for removing design deficiencies/faults, eradicating/minimising equipment maintenance requirements and improving equipment service-ability, in addition to improvement in terms of functionality and performance.

- (c) Integration of extended service support functions for supporting in-service re-configuration/upgrade/expansion for new generation manufacturing systems.

Furthermore, the research has advanced the capabilities of remote maintenance support systems for supporting the proposed service support strategy for new generation manufacturing systems as follows:

- (a) Integration of a refined 3D-based virtual platform/environment (See (3) below.) for improving remote visualisation of complex new generation manufacturing systems. It provides an environment for supporting remote maintenance support and for facilitating the continuous improvement and optimisation of equipment during its in service life (for both equipment performance improvement and, long-term service-ability and maintainability improvement, in addition to improvement in terms of equipment functionality and performance).
  - (b) Integration of a maintenance-support-tool/strategy support environment with the 3D-based virtual platform/environment for supporting the development, testing, assessment and installation/re-configuration/upgrade of automated/intelligent maintenance-support-tools.
  - (c) Integration of a re-configuration/upgrade/expansion support environment with the 3D-based virtual platform/environment for supporting in-service re-configuration/upgrade/expansion of complex new generation manufacturing systems.
  - (d) Integration of a re-configurable maintenance service support system (embedded in the machine system), consisting of a set of automated/partially-automated maintenance support modules, a re-configuration support system for supporting remote re-configuration/upgrade of maintenance support modules and a control system re-configuration support system.
- (3) This research has informed the refinements of the concepts of a 3D-based virtual platform for improving remote access, visualisation and re-use data/information (design, operational and maintenance-related) of complex new generation

manufacturing systems. It was observed that the effectiveness of a remote maintenance tool could be improved via the integration of 3D-based visualisation tools and other visualisation tools/techniques (e.g. 2D-based visualisation tools/techniques, video based tools/techniques etc), for creating an **integrated visualisation environment** consisting of multiple inter-linked 2D/3D visualisation environments. In the proposed system, traditional approaches have been refined to allow it to be used for visualising a mechatronics system from different perspectives (e.g. the mechanical/geometric aspect, electrical/electronics aspect, control system/scheme (both the software or hardware aspect) etc). 'Inter-link' is set up in such a way that each visualisation environment consists of virtual objects (each of which is associated with a particular component of a mechatronics system), which are interactively linked with the corresponding/closely related virtual objects in other visualisation environments (See sub-section 5.3.3.2 for details.).

- (4) A set of requirements for a more cost-effective and comprehensive advanced machine service support strategy/system for new generation manufacturing systems has been identified. The focus of the requirements specification is on answering the need for: (1) streamlining conventional maintenance support functions, and (2) extending the range of conventional maintenance support services, in such a way to allow for more comprehensive life cycle support for new generation manufacturing systems.
- (5) A prototype based on the proposed framework has been implemented to demonstrate and explore the main concepts of the proposed strategy/system. It consists of a set of integrated modular network-ready software tools consisting of: (1) an integrated 2D/3D visualisation and analysis module, (2) support tools library modules, (3) communication modules and (4) a set of modular and re-configurable data logging, automated maintenance and re-configuration support modules. A number of test cases based on various machine service support scenarios, have been conducted using the prototype. Whilst the prototype system formulated is rudimentary in terms of functionality, it has shown the potential of how a 3D-based virtual environment can be used to provide a 'virtual integration

platform', for facilitating the embodiment and coordination of various service support functions (both conventional and extended in nature).

## **8.4 Conclusions**

This research study has contributed to a better understanding of how a 3D-based virtual environment can be used as an integration platform, for an advanced service support strategy/system for new generation manufacturing systems. A conceptual framework for a novel integrated remote service support strategy/system, for new generation manufacturing systems, has been proposed in this thesis. Laboratory experimentation using a prototype based on the proposed framework has shown the potential of the proposed approach as a strategy for improving existing machine service support strategies/systems for new generation manufacturing systems. However, due to the limited scale of the laboratory test bed, further development and experimentation based on an industrial-scale test bed is required (Refer to section 8.5 for further details.). The outcomes of this study have provided a foundation for such future research and development work.

## **8.5 Recommendations for Future Work**

The following aspects have been identified as requiring further research and attention, but being beyond the scope of this study:

- (1) Further research into the integration of the proposed system with different 'open' controller architectures such as the Open Environment Control, Open Environment with Common Interface Control and Open Modular Architecture Control (GMPTG OMAC, 1996; OMAC, 2005). This is required to gain insight into how to streamline the data/information acquisition and control system components re-configuration/upgrade/expansion process. The work should identify the following:
  - (a) Optimised strategies to ensure that the implementation of the service support system would not cause any significant impact on the design and performance of the machine system. It is important to ensure that failures



in either system will not result in subsequent failures in or disruptions of the other.

- (b) Optimised strategies are required to ensure that the need for additional (i.e. functionally redundant from the perspective of machine control) sensors (and associated signal conditioning/data acquisition components) is kept at a minimum. This can be achieved by effectively leveraging the built-in capabilities of the control system such as built-in data logging functions etc, and exploring other more advanced concepts such as the Virtual Sensor (Discenzo, et al., 2000).
  - (c) Optimised strategies for the implementation of the data acquisition system (which includes sensors, signal conditioning elements and data loggers) to ensure the flexibility of the system in particular in terms of the installation/removal of additional/obsolete components of the data acquisition system.
- (2) Further experimentation with the prototype is required to gain more insight into the proposed remote re-configuration/upgrade/expansion support process. The work should attempt to gain a better understanding of how to take advantage of existing design and software development support tools to facilitate modifications to original equipment designs (both hardware and software components).
  - (3) Further development and experimentation with the user interface for the proposed Integrated 2D/3D Visualization and Analysis Environment (IVAE) for a larger-scale and more complex system. These are required to gain a better understanding of the design aspects of the visualisation environment. Some of the potential refinements have been summarised in section 8.2 and the integration of other visualisation techniques/tools (such as augmented reality).
  - (4) Further development and experimentation with the prototype is required for the proposed Automated Maintenance and Re-configuration Support System (AMaReSS) for a larger-scale and more complex system. The work is required to gain insight into how to more effectively leverage existing support tools (such as various automated monitoring, diagnostic and prognostic tools) and emerging open architectures/standards for condition-based maintenance support systems

(such as the Open System Architecture for Condition-based Maintenance (OSA-CBM, 2005)).

- (5) Further development and experimentation with various data acquisition, storage and transfer strategies, to gain insight into how to more effectively leverage existing network/Internet-based communication technologies. By integrating various communication technologies, it is expected to create a more scalable, flexible, efficient and fault tolerant data/information communication strategy. The various identified potential technologies are: Distributed Component Object Model (DCOM, 2005), Common Object Request Broker Architecture (CORBA, 2005), JAVA Remote Method Invocation (JAVA RMI, 2005), Simple Object Access Protocol (SOAP, 2005), Microsoft's .NET Remoting (NET Remoting, 2005), File Transfer Protocol (FTP, 2005) and Simple Mail Transfer Protocol (SMTP, 2005).
- (6) In addition to the technical aspects, there is also a need to address some of the non-technical issues, as mentioned in sub-section 8.2, under research question 2.

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