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REPORT OF THE WORKSHOPS: AUTOMATED GENERATION OF ELECTRONIC TECHNICAL MANUALS

David L. Zimmerman
Cordell Green

KESTREL INSTITUTE
3260 HILLVIEW AVENUE
PALO ALTO, CA 94304

Dave Gunning
Gary Worrall

HUMAN RESOURCES DIRECTORATE
LOGISTICS RESEARCH DIVISION
2698 G STREET
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-7604

Bert Dimock

DIMOCK ASSOCIATES
701 EAST SEVENTH STREET
SPRINGTOWN, TX 76082

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SANDRA K. SMITH, Capt, USAF
Contract Monitor

BERTRAM W. CREAM, Chief
Logistics Research Division

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David L. Zimmerman
Cordell Green
Bert Dimock
Dave Gunning
Gary Worrall

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Kestrel Institute
3260 Hillview Avenue
Palo Alto, CA 94304

Dimock Associates
701 East Seventh Street
Springtown, TX 76082

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13. ABSTRACT *(Maximum 200 words)*

Paper-based technical manuals are expensive to produce and maintain, difficult to update and modify, and bulky and inflexible in the field. They are fast approaching their practical limit in coping with the complexity of modern Air Force weapons systems. The next 10 to 15 years hold the promise of a revolution, triggered by emerging technologies, in the production and presentation of aircraft maintenance information. This report describes a vision of integrated and electronically based maintenance information support in the future, and suggests the specific research and development goals necessary to achieve that vision. The report identifies a number of emerging technologies which will enable maintenance instructions to be created and managed more efficiently, and used more effectively, than they are now. Outlined herein are the essential advancements in applicable field needed to migrate from a costly and cumbersome world of paper production to the lean world of digital production and delivery. Success in these pursuits will bring enormous benefits both within the economy of human-centered design technology for concurrent engineering and in the performance of maintenance personnel.

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PREFACE

The Logistics Research Division of Armstrong Laboratory (AL/HRG) held a workshop in Palo Alto, California, and a follow-up session at Wright-Patterson Air Force Base to explore emerging technologies which could be applied to the automated production and presentation of aircraft maintenance information. The overall goal of the workshops and this report is to help establish a research agenda for AL/HRG in advancing the coming generation of Interactive Electronic Technical Manuals (IETMs). This will not only serve Armstrong Laboratory in project planning but will also provide a general overview, along with specific guidelines, for prospective research and development teams.

The ideas presented in this report were drawn, over the course of the workshops, from a panel of experts in various applicable fields. These include original engineering design extraction, qualitative reasoning, human-modeling, automated task planning, generation of multimedia explanations, and user interface technology (including virtual reality). Research addressing short-, medium-, and long-term goals is discussed in each of these areas, as well as in emerging technologies which cut across the various phases of technical manual production, such as automated consistency checking and automated validation and verification.

These workshops would not have been possible without the innovative ideas, detailed planning, and overall support of David Gunning at Armstrong Laboratory. Dave's vision and determination continue to be an inspiration to all those involved in the future of Air Force technical manuals. The author also acknowledges the influence of AL/HRG division chief, Bertram W. Cream, and Robert C. Johnson, chief of the Operational Logistics Branch, along with the rest of the staff at AL/HRG, for their assistance in making these workshops happen.

The research views presented here are drawn directly from those of the distinguished participants. The author gratefully credits these experts for their ideas and assessments, which were collected through the scheduled presentations, individual discussions during the workshops, and various notes and suggestions provided afterwards. Bert Dimock, of Dimock Associates, provided much of the introductory material appearing in this report and helped prepare the initial drafts. The technical contributions of Norman Badler, Ed Boyle, Mark Drummond, Steven Feiner, and Gary Worrall deserve particular recognition as well.

Thanks go to Mark Miller and Garth Cooke, of Systems Exploration Incorporated, for competent handling of local arrangements. Jeff Kitson and Maria Pryce of Kestrel Institute helped with filming and various "last minute" details during the first workshop. Cordell Green of Kestrel Institute, and Dave Gunning, along with others at Kestrel and AL/HRG, reviewed numerous drafts and provided valuable feedback along the way. Thank you all.

David Zimmerman

Kestrel Institute
Palo Alto, CA

July 27, 1993

SUMMARY

This report describes the results of a workshop held in Palo Alto, California, (September 1991) and a follow-up session held at Wright-Patterson Air Force Base (March 1992) to explore emerging technologies which could be applied to the automated production and presentation of aircraft maintenance information in digital form. The workshops were sponsored by the Logistics Research Division of Armstrong Laboratory to help establish a research direction for the next 20 years that incorporates concepts being developed in university laboratories and by commercial enterprises.

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REPORT OF THE WORKSHOPS: AUTOMATED GENERATION OF ELECTRONIC TECHNICAL MANUALS

I. INTRODUCTION

The Logistics Research Division of Armstrong Laboratory (AL/HRG) held a workshop in Palo Alto, California, (September 1991) and a follow-up session at Wright-Patterson Air Force Base (March 1992) to explore emerging technologies which could be applied to the automated production and presentation of aircraft maintenance information through Interactive Electronic Technical Manuals (IETMs) . The participants were primarily from universities and research institutes, but also included representatives from both nonprofit organizations and those with commercial products related to the technical manual production process. The purpose of the workshops was to aid AL/HRG in establishing a research direction for the next 20 years that incorporates concepts being developed in university laboratories and by commercial enterprises.

Although the central focus of the workshop, the automated generation of electronic manuals is only one phase of the participants' overall vision of future maintenance information support. A recurring theme of the workshop was that this future must involve the cyclic integration of supporting technologies across a wide spectrum, from original product engineering design and data management, through the presentation of technical instructions and maintenance information to end users.

Within each of the maintenance information production phases (identified below), developmental data is gathered to provide feedback to earlier phases. The potential economies and expected leverage of such integration are key promises in the fundamental transition, now under way, which this workshop addressed. Specifically, the workshops addressed the technological developments needed to move from paper documents largely produced and checked for accuracy by humans, to various electronic sources produced, verified, and validated largely by machine.

Processes and Products

The development of maintenance information for eventual delivery to technicians involves a series of interdependent processes and products. The overview in Figure 1 illustrates the key elements in this development, their current form, and their anticipated form in the near- and long-term future (Gunning, 1991). This figure, particularly the bottom row, provides a rough road map of the specific technologies considered during the workshops.

The blocks in the top row represent processes; the words above and to the right of the blocks describe the output of the processes. The second row shows the form of these products within the current development environment: Engineering output is equipment design via paper which, in turn, serves as input to Logistics Support Analysis (LSA). The LSA process produces LSA records and tables, also via paper, which a technical writer uses to describe procedural task steps, based on the analysis of individual maintenance tasks. Task analysis is a key issue in the integration of LSA with technical data. It is also the key to generating maintenance procedures (more or less) automatically. Continuing the process, an illustrator adds drawings to the text, then the product undergoes Quality Assurance (QA) through visual inspection. Though the author and illustrator each store their contributions digitally, as Computer-Aided Design (CAD) files, the final validated technical manual is delivered to the technician in paper form.

The third row represents what is expected in the year 2000: Engineering produces a digital file, with drawings in the Interim Graphics Exchange Specification (IGES) format. LSA information is also stored digitally, but separate from the engineering data. The writer has access to both databases and produces format-free textual instructions in accordance with the IETM Data Model.[1] Illustrations, as digital graphics, will be linked to the associated text within these databases. QA is performed visually via a simulation screen, similar to the technician's Portable Maintenance Aid (PMA).

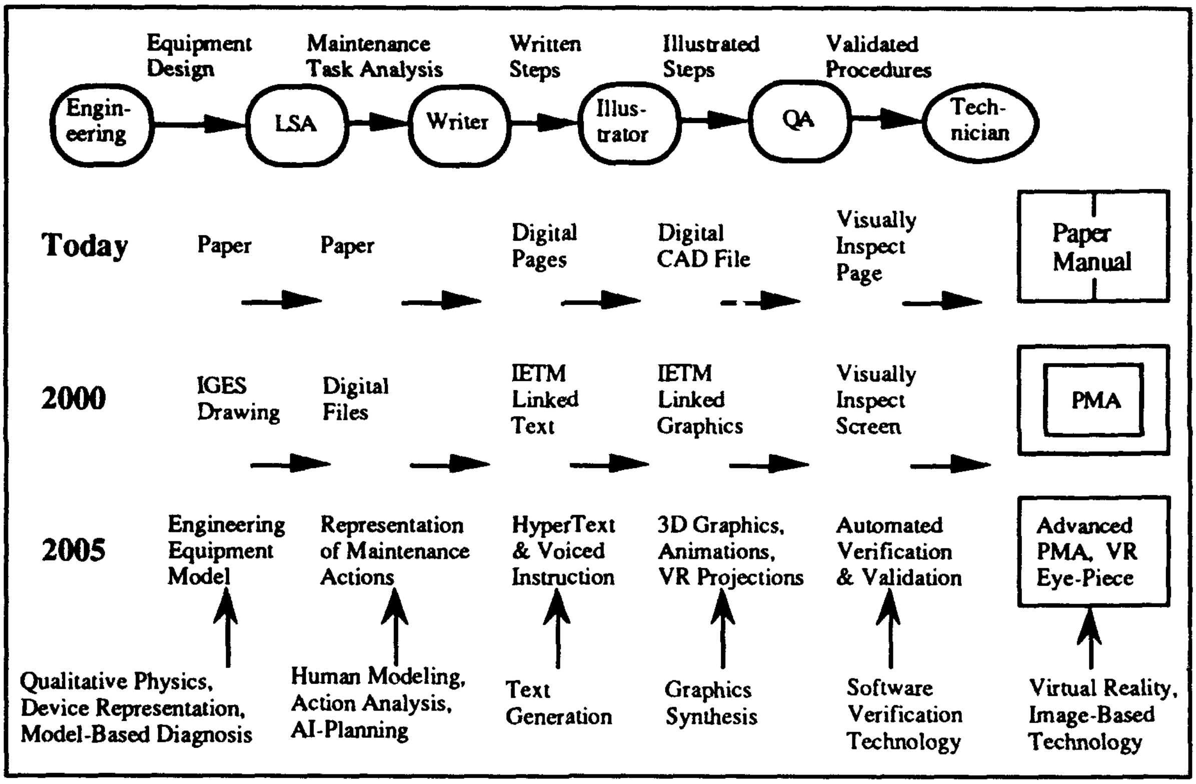

Figure 1
A Current and Future View of Technical Manual Processes and Products

The next row shows the maintenance information products as envisioned within roughly 10 years, the approximate long-range "look-ahead" of the workshops. The text at the bottom notes several of the particular technologies discussed, such as Qualitive Physics, Artificial Intelligence (AI)-planning, three-dimensional (3D) graphics synthesis and Virtual Reality (VR), and automated software verification, which might use and pro-

[1]The IETM Data Model is a database design specification for organizing and cross-referencing various maintenance information elements (Fuller et al., 1991).

duce these products. All these anticipated technologies and their interactions are described in more detail in later sections of this report.

Although the illustration follows the linear (serial) way in which individual phases are performed today, it is expected that the overall process will become increasingly "circular." For example, logistics analysis results will feed back into engineering for design revisions, verification technology may uncover inconsistencies which will trigger regeneration of textual descriptions, and so forth. The collective effect of the successful implementation of these advanced technologies is reflected in the following scenario, presented in the same spirit as the "Sgt. Bayshore" scenario of some 13 years ago.[2]

A Glimpse of the Future

Joe Write had been involved in creating maintenance information for 20 years. His first job as a technical writer was on the F-16, where he had worked for 6 years before being transferred to the F-22 in 1996. Prior to that, he had worked on the environmental control system of the F-16. In those 15 years as a technical writer, he had seen an evolution from paper-based technical manuals to computer-based information delivered as neutral data and displayed on a screen. However, this natural though dramatic evolution did not prepare him for the last 5 years and the even more dramatic changes he had witnessed.

The changes began with the merger of several companies into the National Airplane Company (NAC), prompted by a need to survive in the down-sized world of defense spending, and they continued when NAC received the contract for a successor to the F-22, the F-27. The winning proposal promised to implement, within an integrated production system, results of work sponsored by the Department of Defense (DoD) and its component laboratories since the initial F-22 contracts. The specific elements to be implemented and integrated included:

- A well-defined specification for the interpretation and exchange of product data.
- A mature task analysis capability including human-modeling, planning, and ani mation, based upon detailed knowledge about both equipment and personnel.
- Generation of maintenance information through automated synthesis of text, graphics, and sound.
- Virtual worlds which simulated the aircraft and overall maintenance environment in a realistic 3D space.

On the F-16, Joe had worked with paper source data and interviews with engineers to create his isolated database of maintenance information. Although much of the design had been created on CAD terminals, he could not access it directly. On the F-22, all engineer-

[2]Some 13 years ago a short scenario depicting a maintenance technician named Sgt. Bayshore was written (Johnson, 1981). It centered on the use of a portable computer, to provide technicians with all the information, including technical data, needed to do their jobs. The concept grew into a program now known as the Integrated Maintenance Information System (IMIS) (Link et al., 1987). This visionary approach, divided into achievable research projects, has become the baseline maintenance concept for the F-22.

ing design was performed on workstations linked to a common network; thus, all this design information was available to Joe. LSA data was created similarly and was also directly available.

However, most information was still developed serially; engineering finished the design before LSA was accomplished, and LSA had to be completed before Joe could create his information. Validation of maintenance information had also changed on the F-22 contract, but engineers and technical reviewers still had to step through the procedures to assure their accuracy.

Joe considered the F-27 requirements to be an order of magnitude beyond those of the F-22. Design engineers no longer created systems in isolation. Every component, subassembly, and assembly underwent an early, automated analysis of what was required to build and repair it. If the analysis uncovered problems with the design, AI-based software would propose a solution. Automated human or machine models could be animated, graphically enacting the manufacturing and/or maintenance problems discovered. In some instances, the designer was able to put on a sensor suit and helmet and enter a virtual world which simulated that of the technician.

Joe had witnessed the evolution of logistic support analysis from a single discipline, overseeing design as it impacted logistics requirements, into a collection of interrelated programs and databases which provided more immediate and much more rigorous analyses. Interim evaluations accompanied each design step rather than being performed after the fact. One major benefit Joe observed was the tremendous reduction in paper products, previously necessitated by design and LSA specifications, as well as contractual delivery requirements. These changes affected his job in several ways.

- He no longer directly created text; it was generated as a product of design and computer-aided task analysis. Using standardized style libraries, both text- and voice-based procedural descriptions could be generated to address a variety of technician skill levels and maintenance contexts.

- No illustrators were needed; most equipment diagrams were generated from en gineering data and CAD graphics. The automatic planning programs which gen erated the procedures also extracted or synthesized supporting illustrations from design drawings and structural specifications.

- Certification of procedures, which earlier meant validation through human "walk-throughs," was largely automated. Specialized software, drawing upon a knowledge base of consistency requirements and presentation rules, now supplied formal validation and verification, assuring that the appropriate information would be correctly sequenced and displayed during any potential maintenance scenario.

Though Joe reviewed the procedures and supporting illustrations, the detailed testing was all done by machine. If he found problems, he met with the responsible designers and programmers. Together they worked out solutions and changed the certification system knowledge bases as required.

As Joe was relieved of these more mundane tasks, he was given a new one: the performance of maintenance procedures in a computer-generated environment. Donning a sensor-suit, complete with gloves and helmet, and connected to a simulation computer, he experienced a virtual reality in which he removed parts according to instructions and repaired or replaced them as necessary.

The computer-generated models displayed on his visor appeared real. Tactile sensations were created by his gloves; sounds of the flight line embellished the illusion. If a task required two people, another acting "technician" also put on a suit to assist. Both Joe and his peer were in the same "world," seeing and hearing each other as if it were real.

This VR world also allowed Joe to act as an "author." As he physically performed tasks on the virtual aircraft in the virtual world, the computer recorded his motions, generating a series of steps which constituted the procedure. In both cases, the product knowledge base supplied the engineering detail for the 3D equipment renderings.

Joe's individual responsibilities were not the only logistics elements which underwent dramatic change on the F-27.

- Staffing of spare parts personnel was reduced to a fraction of earlier needs, since spares were automatically identified by maintenance levels and quantities.

- Training became part of the Information Monitoring Group of which Joe was a member. Equipment mockups were replaced by VR models.

Technician training still consisted of both diagnosing problems and performing maintenance procedures, but training media was again generated from engineering and CAD sources. Equipment simulations required for training could be generated in a virtual world, eliminating the need to construct physical "mock-ups." Virtual overlays and "x-ray" views supported diagnosis and troubleshooting. The suspected component(s) of a given subassembly could be highlighted with colors corresponding to their fault status; internal details could be "seen" beneath the surface.

Actual maintenance performance was similarly supported by such capabilities, including view rotation, interactive zooming, and animation. The technician's PMA screen gave way to "heads-up" displays and "see-through" VR goggles, which could show exploded and rotated views of the individual parts of a complex (real) component as he looked at it. Descriptive information, such as operational theory, was also delivered in this way. Internal mechanics and fluid flows could be animated, to appear above the (real) assemblies being examined.

The changes Joe and his co-workers experienced did not happen overnight. They were based on incremental milestones developed as part of a total vision. Individual projects were funded at various university, commercial, and defense laboratories and orchestrated by a central office. Interim results from each project were constantly evaluated for impact on other projects, and appropriate changes made. The outcome appears to be magic. It isn't. It is only the application and extension of existing capabilities toward a visionary goal.

Organization of the Report

The remainder of this report is organized into five sections. Section II provides some background by examining the foundations of the technical manual production process as it exists now on the F-16 and as it will be implemented on the F-22. The F-22 approach is the baseline from which newer concepts, discussed in this report, will be developed. Those already familiar with IMIS and the current "state of the art" in technical manual production may wish to skip or briefly review this section.

Section III introduces the applicable technologies, as presented during the first workshop. Each technology area is defined and briefly overviewed. Section IV continues presentation of the first workshop's results with suggestions for short-, medium-, and long-term research and development milestones. The suggested milestones are collected under three principal areas for advancement, corresponding to the three basic phases of maintenance information support presently identified. These sections thus extend and generalize current concepts and activities regarding: (i) acquisition of engineering source data, (ii) technical authoring, and (iii) presentation to the technician/user.

Section V summarizes the results of the first workshop, abstracting several key themes which emerged. Section VI provides an initial research agenda. The specific project items of the agenda were derived from the second workshop, in which a subset of the original participants gathered to narrow their focus and agree on a program for prospective funding.

II. FOUNDATIONS: CURRENT AND NEXT GENERATION

Technical manuals, termed technical orders (TOs) by the Air Force, are the only official source for information on how to operate, diagnose, and repair equipment. TOs constitute a major expenditure during the operational life of a weapon system. The costs associated with TO development, maintenance, updating, distribution, storage, and transportation have increased dramatically for several reasons.

- Equipment has become more sophisticated, particularly with the introduction of on-board computers.
- Specifications covering the content and format of the manuals have evolved, re quiring more detailed coverage directed at less experienced technicians.
- The advancements cited above have led to a requirement for more pages and more manuals.

Figure 2 shows the basic steps in technical manual preparation. Source data is used by the author to generate the information, which is then delivered to the user. Creation of the manuals involves three major elements: textual instructions, illustrations to support the text, and the merging of text and illustrations to produce the final pages of the TO.

Figure 2
A High-Level View of Technical Manual Preparation

Historically, TO text has been written by authors having expertise in a specific field (e.g., electronics, hydraulics, structures). Design and manufacturing information served as the primary source data, augmented by dialogues with engineers. The manuscript was either typed or handwritten.

Illustrations necessary to support the text were either sketched by the writer and given to an illustrator or verbally described. The illustrator, working at a drafting table, prepared the illustration using lettering pens, templates, "rub-ons," and other artistic devices.

When both writer and illustrator completed their work, information was passed to a production department. Here the text was prepared on a type-setting device, and the output was pasted onto page layout sheets and integrated with the illustrations as appropriate. The front matter was prepared by the production department after all changes required by the writer and/or quality control personnel were made. Finally, the completed pages were sent to the printer where the deliverable product, printed pages or negatives, was prepared.

Current Approach (F-16)

With the advent of the F-16, increasing complexity, both in the equipment and level of detail in TO specifications, forced contractors to find ways to produce the increasing number of pages in a timely manner and at an acceptable cost. This was accomplished by (separately) applying computer technology to each step in the process.

- Writers were given computers or computer terminals, where their text was cap tured and used by the production personnel. Handwritten or typed manuscripts virtually disappeared.
- Illustrators were given either CAD or specialized illustration terminals on which to prepare the artwork.
- Production personnel were given page-layout terminals on which the text and il lustrations could be merged within a template which complied with the particular specifications governing the TO.

Though successful, this sort of "office automation technology" failed to produce the expected gains in productivity used to justify its implementation costs. The cognitive process preceding the actual text creation, illustration sketch, or page preparation was still largely unsupported.

A major fault with the F-16 approach was "automating" the three processes independently. Authors with character terminals could not access the illustration for an electronic review. Illustrators could not access the text which their drawing supported; they could not see it in context. Neither group could see the final page as it was laid out by the production staff.

Another major fault was that the technical manual department was "automated" independent of all other disciplines—engineering, manufacturing, etc. Department personnel still used paper products as their source data, manually converting it to digital form in their own machines, and thus creating a largely redundant database.

The new specifications meant that an F-16 technician (the end user of the products) received hundreds of technical manuals containing tens of thousands of pages. Although these did contain the information he needed to do his work, the information was frequently hard to find, thus increasing the man-hours required to repair an aircraft.

The cost of a TO library, with attendant personnel, also increased. The numerous TOs required more storage area and were repeatedly updated with hundreds of changes. A subset of the library had to be packed for field deployment, occupying much of the volume and weight required to support the move.

Next Generation Approach (F-22)

With the next generation aircraft, maintenance information processes will become more integrated and less redundant. On the F-22, designers and authors will be able to access technical databases and use the (source data) information created upstream from them. The following paragraphs describe several facets of the planned approach.

Design

Design of a weapon system (aircraft and/or support equipment) will be done exclusively on computer terminals. A database containing all drawings for manufacturing will be generated, with bills of material, parts lists, etc., available as ASCII files. Most of the design illustrations will be 3D, based on underlying solid models.

Integrated Logistics Support

Integrated Logistics Support (ILS) will operate as an integral part of design engineering. It will identify ways in which design changes can improve both supportability and the resources needed to support a fielded system (Jones, 1991). ILS disciplines include:

- Maintenance Planning
- Supply Support
- Technical Data
- Facilities
- Manpower and Personnel
- Training and Training Support
- Support Equipment
- Computer Resources Support
- Packaging, Handling, Storage, and Transportability
- Design Interface

The findings of the ILS disciplines will be recorded in a database which can produce reports or electronic views of the data. This is the idea of the Design Evaluation for Personnel, Training, and Equipment (DEPTH) program (Boyle, 1991). The database will include identification of maintenance tasks, steps to perform those tasks, personnel requirements, expected completion time, required equipment, and other pertinent information, all of which will be directly usable in the maintenance instructions.

Technical Authoring

Technical manuals will be created on high-resolution terminals with graphics capabilities. The writer will be able to access the ILS and design databases via windows, and copy information needed to complete a task. This is a foundation of the Integrated Maintenance Information System (IMIS) concept (Link et al., 1987). The writers' database will have aspects of a hypertext-like architecture but will be custom-designed to comply with the delivery requirements of a format-neutral database.

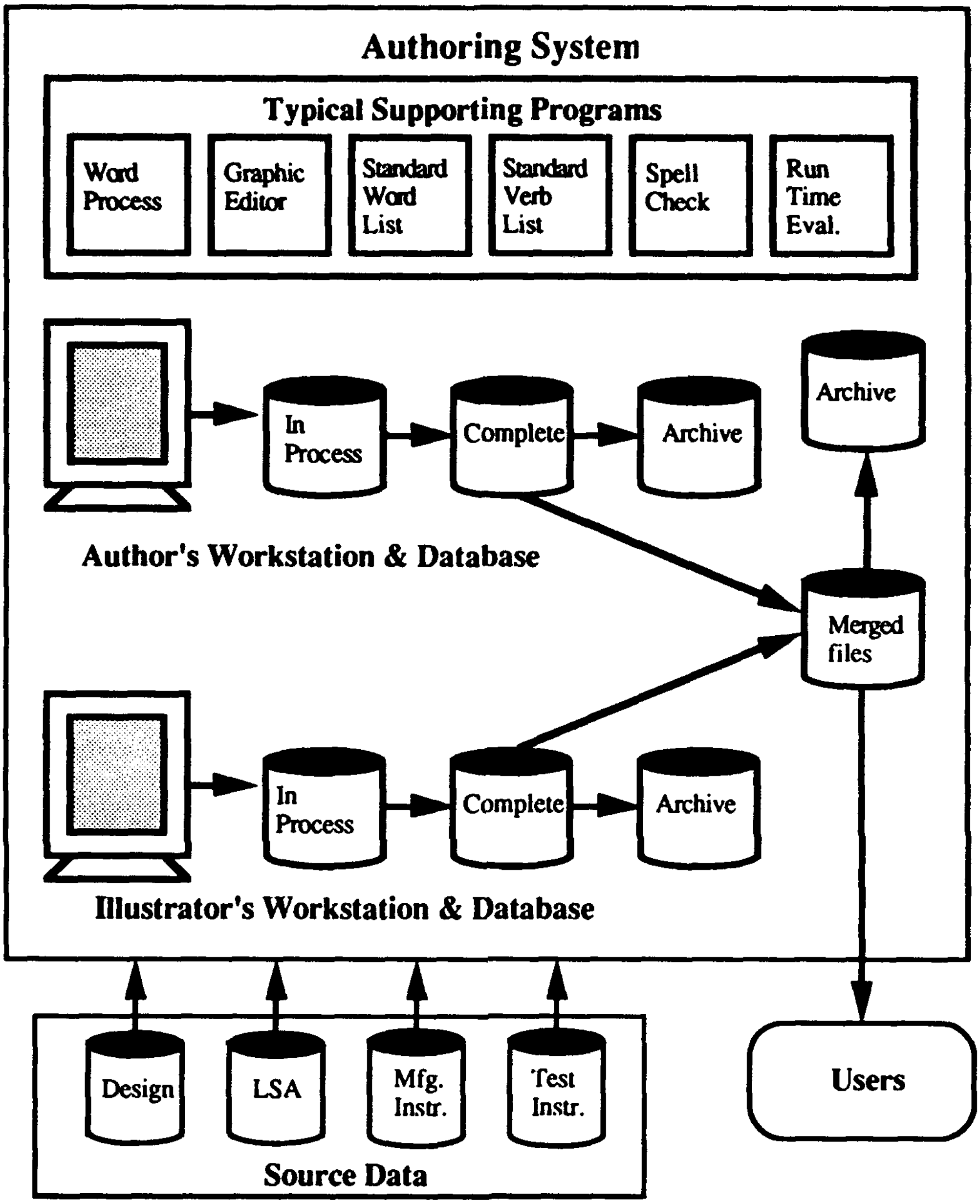

Figure 3
Maintenance Information Creation—Integrated System Concept

Figure 3 illustrates the integrated IMIS authoring system in which the writer (and illustrator) will be supported not only by a sophisticated word processor but by programs such as the following.

- Graphics Editor: A primitive graphics capability (compared to the illustrator's) which allows engineering drawings to be accessed, copied, and changed as re quired. Rudimentary sketches can also be created for submission to illustrators.

- Standard Word Lists: Programs which check that procedural instructions are consistent and use only approved and standardized terminology and action verbs.

- Reading Level Support: Programs to check word and sentence length to assure that the reading grade level of the information does not exceed that of the target user. Spelling checks and on-line correction will also be available.

- Run-Time Emulation: Emulation capabilities will allow the writer to view a pre sentation of the authored text/graphics, just as a technician would view it during a maintenance scenario. This helps assure the writer that the information has been created properly, linked with appropriate graphics, contains cautionary information in the proper places, and so forth, as required by presentation specifications.

The illustrator will have access to writer-prepared sketches, design files, and a library of previously prepared illustrations. Through windowing he will be able to copy any file, and merge and make changes as required to support the overall technical presentation.

The writer and the illustrator will each have in-process files, to which they alone have access. When they have completed their tasks, the work is moved into another database where it is subjected to quality assurance and validation requirements as a completed document. When these processes are finished the merged file is delivered to the customer/user and archived. The writer's and illustrator's files are also archived, independently of the merged file(s), for future reference, copying, or modification.

Electronic Presentation

The culmination of these efforts is delivery of information, describing how to perform maintenance actions on a specific system, to a given maintenance technician. On the F-22, information will be delivered via the electronic display of a PMA. The information will be selected and filtered for his specific system and its particular configuration; he will not have to sift through screen displays which do not apply to his current situation. He will be given information appropriate to his level of training and experience, eliminating the paper-based problem of targeting the presentation to the lowest skill-level technician.

The availability of maintenance history, similar to that which a doctor has regarding a patient's medical history, is another important feature. This will allow the technician to see what has previously been done to his "patient" to solve the same or similar problems. If a technician encounters difficulties with some segment of the presentation, he can electronically "mark" it so that it can be analyzed by the contractor for accuracy. If he is certain about the error he can create a "note" or "bookmark" to which he will automatically be alerted the next time he runs the procedure, if it has not been officially corrected.

The PMA will maintain an audit trail of the technician's activities: the path he followed through the information, how much time he devoted to particular screen displays, and what maintenance actions he performed. This information, along with that of other technicians, will be up-loaded into a central database where it can be analyzed to determine possible deficiencies in either the information supplied or the technician's effectiveness. If a significant number of technicians experience the same types of problems, the information may be re-analyzed for understandability. If a particular technician establishes a pattern of not understanding the presentations, additional training may be recommended.

These are all substantive improvements to the process of technical information creation and delivery, and will increase both production efficiency and presentation quality. However, they are by no means all that may be envisioned and planned for. A number of emerging technologies, if properly developed and applied, could support even greater changes, such as (a) complete, standardized engineering and logistics information; (b) maintained and updated information throughout a product's service life; and (c) automated generation and correctness certification of sophisticated multimedia presentations. These benefits could be derived through the use of sensory enhancements verging on the dream-like—mechanical animations, dynamic overlays, holograms, and virtual reality.

Building upon the foundations described above, the first workshop identified a number of research directions essential to maintenance information support in the generation to follow. By extending and applying current work in these areas, we can take the first steps toward Joe Write's world.

III. TECHNOLOGIES FOR THE FUTURE

Future maintenance information support, as envisioned for the year 2000 and beyond, depends on the integration of a range of individual technologies to extend the baselines described above. Accordingly, the workshops brought together a number of leading experts in some of the emerging technologies thought to be most crucial.[3] In addition to the presentations of current work in each specific area, several group discussions during the first workshop afforded participants the opportunity to place their results within the overall context of maintenance information and electronic technical manuals and consider how their techniques might be composed with other advances.

This section overviews each area of the technology addressed and where it fits within the overall development process. Several of the technologies overlap, some have potential application in more than one phase, and others apply across the production cycle (e.g., integrating or quality assurance technologies not closely associated with any specific process or product). For instance, software consistency checking and certification techniques are applicable to all phases of electronic TO production.

The technology areas specifically addressed during the workshop were:

- Product Data
- Qualitative Physics
- Automated Planning
- Human Modeling
- Automatic Text Generation
- Graphics Synthesis
- Automated Verification
- Virtual Reality

The workshop also reviewed existing processes and procedures for ILS/LSA, including management of technical data. The following paragraphs give a short description of each area; more detailed discussions may be found in the papers listed in the references.

Product Data

Product data, in its fullest sense, denotes all the data elements which define a product for all applications over its expected life cycle, where life cycle includes design, analysis, test, inspection, and product support. The data elements required include geometry, tolerances, material properties, surface finishes, logistics support information, and other attributes and features that completely define a component part or assembly.

[3] A list of the participants, and a brief biography of each, is presented in the appendix .

A major effort is under way to define product data in a specification entitled Product Data Exchange using STEP (PDES), where STEP is the Standard for The Exchange of Product data (Wilson, 1991). PDES is intended to result in a national standard compatible with STEP. The primary objective of PDES is the development of a standardized, neutral, computer-based definition of product data which supports the "seamless," integrated use of product data for different applications.

Product information consists of not only data, but the relationships between data and the meanings attached to it. The fundamental concept of PDES is the standardized representation of (directly) computer-intelligible information and interrelationships, versus data which becomes information only because it is human-intelligible. PDES is directed at providing both the rationale and formal foundation for information extraction from product data.

Qualitative Physics

Qualitative physics addresses reasoning about the physical world, with the goal of capturing both the "common sense" mechanical intuition of humans and the quantitative descriptions of classical physics (Forbus, 1988). The hope and intent is to achieve a degree of systematic coverage and uniformity far in excess of today's knowledge-based systems. Expert systems today contain encoded knowledge about a particular domain for a particular purpose, while qualitative physics strives to create wide-coverage, multipurpose domain systems.

Current concerns in qualitative physics include *dynamics* (what causes systems to change over time), *kinematics* (the spatial reasoning of mechanical common sense), and *reasoning styles* (ways to exploit the knowledge in such areas as qualitative simulation, envisioning, recognition, and measurement interpretation) (deKleer, 1989).

Potential applications for qualitative physics exist in automated planning, particularly in the generation of procedures. The design of new hardware needs to incorporate the information necessary to generate maintenance procedures automatically, develop procedures for operating it, diagnose its failures, and repair it. As computers are enlisted to generate complex hardware designs, they can also begin to generate the supporting information.

Automated Planning

Automated planning concerns the generation of a plan, or composition of procedural steps toward a goal, which is one possible solution to a particular problem. The individual steps are typically *operator schemata*, each of which characterizes a class of possible actions (Hendler et al., 1990). Instantiation of the variables defined by an action class produces a specific action for a given situation, according to the substitution values the situation implies.

In general, the input to an AI-planning system is a set of operator schemata appropriate to the application domain and a *problem*, characterized by an initial-state description and a goal. The initial state describes the planners "world" as it is, and the goal describes how it should be after execution of the plan. The goal is often made up of several subgoals (Sacerdoti, 1975).

A plan is a solution to the problem if the plan is *applicable* to the initial state and after plan execution, the goal is true. A plan (or subplan) is applicable if all the preconditions for the execution of its first operator hold in the current state. Repeated analysis of the required preconditions, across the composed effect of applied operators, (termed "temporal projection") can determine whether all operators may be applied in order, starting from a given initial state.

Human Modeling

Human models are simplified representations of human figures implemented with computer-graphics tools. Such models are often used with CAD systems to help evaluate the ergonomic qualities of potential human/machine designs. Physical human factors such as body fit, reach, strength, and movement can be evaluated with these models before equipment fabrication begins.

Advances in computer technology will allow a much wider array of human factors to be captured in the near future. The best features of the best-known human models, *Jack* (Badler, 1991) and *Crew Chief* (Easterly & Ianni, 1991), are to be combined in a "super" human modeling system under the DEPTH program (Boyle et al., 1990). Animated models controlled by natural language "scripting" should provide a powerful visual adjunct to automatic generation and validation of maintenance procedures.

AI-planning tools are central to both the animation of human forms and the generation of procedural descriptions for maintenance tasks; indeed, the specific tools required may be identical. In the future, human-model animations might be used directly in maintenance illustrations and will provide a "reality check" for automatically generated procedural descriptions. The DEPTH program intends to approach this from a different perspective. It is possible that the planning models produced by animation technology can provide the basis for generating procedural descriptions.

Automatic Text Generation

The goal of automatic text generation is (ultimately) to eliminate dependence on human authors for maintenance task descriptions. Instead, natural language instructions, tailored to the situation at hand, will be mechanically generated to explain each part of the maintenance task. This is a key step towards decreasing the production costs and increasing the flexibility and customization of maintenance information delivered as text.

As presented at the workshop, automatic text generation is closely related to automated planning. In this case, a plan is constructed for the information content of an explanation, detailing the kinds of information to include, and their sequencing for the particular purpose (i.e., explanation "goal") involved. The plan schema is represented as a graph, which can be traversed to select particular content elements from a knowledge base for the object being repaired. A text generator then produces English sentences from the hierarchy of content elements.

Natural language generation involves the interaction of both syntactic and semantic constraints, such as the "voice" of the sentence to be produced (e.g., active or passive), agreement between subject and verb, the context established by previously generated sentences, and so forth. For equipment maintenance, standard word lists of preferred verbs, nouns, and modifiers should simplify the word selection problem. Within a given display (screen), selection of supporting graphics may introduce constraints on text generation as well.

Graphics Synthesis

As with text generation, graphics synthesis aims to replace human illustrators with software modules that will produce appropriate equipment diagrams, wiring schematics, and so forth, to supplement the text. A content plan can again be constructed to specify the communicative goals of a requested illustration. A knowledge base of geometric shapes, organized with respect to the hierarchy of equipment parts, provides the basic illustrations for mechanical assemblies and subassemblies. A rule-based component controls the composition and evaluation of possible illustrative styles regarding viewpoint and perspective, shading and highlighting, use of insets or "cutaways," and the like. The final illustration is achieved through a generate-and-test approach, with backtracking to earlier (partial) achievement methods when incompatibilities arise (Seligmann & Feiner, 1989).

Another rule-based approach demonstrated at the workshop involves successively transforming expressions in a data description language, through corresponding expressions in a visual description language, and, finally, rendering them on the display screen (Westfold et al., 1990). The data description language expresses unformatted relational information, such as might be found in product databases, and the visual description language includes region primitives such as shape, color, and position as well as various constructors and combining forms. Flexibility in the individual choices of visual representation for data relation allows, for example, synthesis of either (or both) a table or "box and arrow" diagram for some relational expressions.

In general, rule-based approaches permit the encoding of human factors constraints as well as specific display hardware limitations or strengths. Such elements can change over time or for different maintenance situations.

Automated Verification

The Air Force originally encountered software testing issues in developing Operational Flight Programs (OFPs), which run onboard the aircraft and have historically been concerned with aspects of navigation, weapons delivery, flight control, and similar aircraft operations. Due to flight safety concerns, rigorous specifications and procedures have evolved to assure the accuracy of such programs before they are loaded onto actual aircraft. However, since testing of OFPs is primarily done on aircraft simulators (by humans), the resulting quality assurances are largely subjective.

The term *automated verification* is used to distinguish formal rule- and logic-based inference methods performed by machine from the informal reviews (traditionally termed *validation* and *verification*) performed by human contractors and customers. Automated verification systems typically attempt to generate a formal proof that the product (generally software), in some well-defined sense, satisfies a given formal specification.

Though such mechanical certification has been notoriously difficult for software of any appreciable size and complexity, the task can be made more tractable if behavior is restricted to forms with appropriate foundations for mechanical logic (Wang & Goldberg, 1991). Similarly, validation (establishing the internal consistency) of, for example, a database of maintenance information, can be feasible if the structure of the database and desired characteristics of the stored information are amenable to description through formalized rules.

Virtual Reality

Virtual Reality (VR) is an artificial environment perceived by a person wearing stereo eyepieces, earphones, and (perhaps) a fully sensored suit of clothing, all of which are connected to computers and act as peripherals. The computer generates sights and sounds (i.e., a sensory environment) which seems virtually "real" to the user.

The idea is to view a human as a biological mechanism with inputs and outputs—sight, hearing, touch—and to develop a strategy for providing consistent stimuli which cover these sense organs. When successfully implemented, the person has the sensation of being in the computer-generated world, experiencing peripheral vision, real-life sound, and tactile sensations. The environments created today are mostly cartoon-like, lacking the details of the real world, but are becoming less so every year. Texture and radiosity (selective lighting) have recently been added, and detail can be increased as required, based on available computing power.

With respect to maintenance performance, the use of "see-through" VR goggles (or possibly "heads-up" display visors) is envisioned, rather than enveloping the technician in the virtual world. Such devices could provide VR images showing internal mechanical details, subassembly explosions and/or rotations, or operation animations, superimposed on (or above) the real-world components upon which the user focuses his gaze. The identification of such component foci might be done manually by user input or automatically via miniature video input devices (attached to the goggles) and associated image recognition software.

Although sometimes viewed as a futuristic promise, VR is already both a government and commercial success. It is being used by the National Aeronautics and Space Administration (NASA) to simulate planetary exploration and by the military to train pilots, tank commanders, and soldiers. It has commercial applications in medicine, architecture, and education, to name a few. Even in its infancy, VR has significant potential for application in the world of aircraft maintenance. The potential is limited by only two things: the vision for its application and the computing power to implement that vision.

Maintenance *diagnostics* (i.e., fault isolation), a large topic in its own right, was not specifically addressed as part of the workshops; however, it did arise in panel discussions because of its obvious importance in maintenance procedures. Product *design* was also not directly addressed but, similarly, came under consideration with respect to its interaction with logistics analysis.

IV. RESEARCH AND DEVELOPMENT MILESTONES

To attain the maintenance information support "vision" described in the first section (Joe Write's world), advances must be made in a number of specific areas. This section presents a collection of research and development milestones, organized within three principal categories, which may be regarded as research thrusts for the future. The approximate time frame for these milestones is:

- **Short Term:** 1 to 3 years.
- **Medium Term:** 3 to 5 years.
- **Long Term:** 5 to 7 years, subject to availability of underlying technology.

Within each category, the corresponding subsections below first overview the broad area addressed, then outline potential short-, medium-, and long-range research goals within particular subareas. While it is recognized that the necessary integration and information feedback also tend to blur the separation of individual phases, the subheadings roughly partition the field along the classic divisions between engineering data acquisition, technical authoring, and delivery to the technician. They suggest the extrapolation of these fundamental processes in the future.

Integrated Product Development

The basic activity of acquiring and analyzing engineering source data (in order to develop maintenance procedures) has been the province of LSA. LSA refers to an integrated analytic process, with four specific goals:

- Influence design engineering,
- Identify problems and cost drivers,
- Develop support resource requirements, and
- Develop logistics support database

In accordance with the future vision of increased integration and feedback between logistics analyses and design iterations, this report expands the general discipline of engineering data acquisition to "Integrated Product Development," emphasizing (as in *Concurrent Engineering*) the envisioned close connections between engineering design and various forms of product analysis and evaluation, including LSA for maintenance information.

There was general agreement among workshop participants that significant advances in this area will depend and draw upon some form of integrated and comprehensive *Product Knowledge Base* (PKB). More than just a common-access database, the PKB provides persistent and standardized information models used concurrently by product engineering/design and support analyses, as well as supporting Computer-Aided Manufacturing (CAM).

The PDES/STEP endeavor, which aims to standardize information modeling and exchange throughout the entire product life cycle, may be viewed as moving towards such a PKB. To adequately support the emerging analysis technologies discussed in this workshop (e.g., qualitative physics, computerized human-modeling, and AI-based planning), their information requirements and products must be taken into account during the development of PKB standards for the future.

The following subsections collect potential short-, medium-, and long-range goals within product development and LSA. First the PKB is considered, then the complementary topics of engineering analysis and task analysis.

Product Knowledge Base

The overall goal of the PKB is to provide a rigorous formal foundation for instantiation and exchange of product information. It must be complete and comprehensive, encompassing such "known" elements as geometric solids, mechanical and electrical models, maintenance task simulations, and so forth, as well as new technologies when they arise. Information will be represented in a neutral internal form for communication between a variety of diverse systems, and will presumably be based upon one or more conceptual schemas, independent of any particular implementation environment(s).

Short Term

- *Maintenance Requirements Definition*

  Outline some initial problems and issues from the maintenance domain to provide a focus for preliminary research work. Select an appropriate area for concentration, such as qualitative physics to support diagnosis and repair.

- *Data Representation and Translation*

  Investigate the potential for the intertranslation of engineering source data between existing product description languages and databases (such as Express (Wilson, 1991)). Determine if this is a practical long-range approach; apply what is learned to begin development of standard conceptual schemas.

- *Formalisms for Decision Support*

  Study the suitability of various existing formalisms for encoding a select set of maintenance tasks. Focus on planning and decision issues including uncertain action outcomes, inspection tasks, and task hierarchies. Investigate possibilities for accommodating these notions within a uniform PKB.

Medium Term

- *Subsystem Model Development*

  Develop isolated but complete logistics-oriented models of several aircraft components and/or subsystems. Use these small examples to better understand what the modeling requirements are and how to scale up to larger systems.

- *Engineering Change Analysis*

  Establish dependency links between CAD models and graphics (for example). Study how a decision-support tool might be used to perform change analysis. Investigate the use of dependency records associated with planning to track how changed design decisions affect other aspects of a maintenance task.

- *Knowledge Base Consistency Monitoring*

  Develop some simple semantic connections between different representation schemes within the PKB. Investigate the application of automated validation techniques to search for and identify potential inconsistencies.

- *Information Access - Analyzer's Apprentice*

  Develop graphic interfaces and simulation facilities to access information from the database and answer simple "what if" questions. Build a prototype learning component within the decision-support system to act as an advisor/apprentice.

Long Term

- *Comprehensive System Modeling*

  Develop several complete, integrated, hierarchical system models. Abstract an appropriate model for a given application directly from design engineering information.

- *Decision Automation*

  Automate the capture and combination of essential elements of both quantitative and qualitative system models. Attempt to automate appropriate decision-making knowledge. The learning apprentice suggested above provides an appropriate starting point.

Engineering Analysis

Logistics analysis with regard to maintenance support may be thought of as considering particular forms of man-machine interaction. This heading addresses the machine component; that is, analysis focused on the equipment itself. Engineering analysis involves such notions as reliability and criticality of individual components, prediction of failure modes, and effects to the system as a whole.

In the future, engineering analysis will be based more directly on original engineering design data, and will draw more heavily upon qualitative physics techniques. Identification of maintainability problems should occur early for feedback into the design process, perhaps with expert-system advice for modification.

Several problems arise in the use of qualitative physics for LSA engineering analysis.

- Teleology — developing a higher of level understanding of component purpose and operational theory.
- Spatial Reasoning — simulation and/or encoding of human mechanical insight about part shape and function.
- Total Economics — encompassing costs of diagnosis, repair, training, reason ing, and so forth within a common framework for comparative analysis and trade-off.

As with most of the emerging technologies which draw upon engineering data, design diagnosis and "debugging" based on such techniques will require sophisticated formal models for the capture and analysis of design rationale.

Short Term

- *Algorithmic and Causality Analyses*

  Extend existing forms of failure prediction and criticality analysis, using quantitative product data and current statistical and *simulation* techniques to establish causality connections, malfunction effects, and diagnoses.

Medium Term

- *Engineering Design Critic*

  Develop an expert-system-based design "critic" for reliability analysis and evaluation of implied maintenance requirements.

- *Qualitative Predictions*

  Begin to apply qualitative physics reasoning to the prediction of component failures and expected effects, both local and global. Use the results to guide diagnosis tree construction.

Long Term

- *Model Integration*

  Integrate and represent the dependencies between physical modeling from engineering graphics, qualitative physics, and AI-based planning models.

- *Alternative Elaborations*

  Develop simulation and reasoning/analysis support for "what if" questions regarding alternative engineering design paths.

- *Engineering Redesign Agent*

  Extend the expert system "design critic" to an active redesign agent/advisor able to suggest engineering workarounds to predicted maintenance problems.

Task Analysis

Task analysis addresses the human side of the maintenance equation. The primary goal of task analysis is tne generation of maintenance task plans from product data. Representative elements within this heading include proceduralization of specific repair tasks, and analysis of manpower and skill-level requirements.

Computer-based human-modeling systems for task simulation and performance analysis will assume a greater role within LSA. One such system, described and demonstrated at the first workshop, is *Jack*, a 3D graphics system for definition and animation of simulated human figures (Badler, 1991). Built on a sophisticated representation for articulated figures, including joint constraints and strength models, *Jack* offers the human factors engineer or ergonomics analyst a wide range of capabilities for human performance assessment. The DEPTH program, also described at the workshop, intends to combine the best features of both *Jack* and *Crew Chief*, another well-known human-modeling system (Easterly & Ianni, 1991).

Workshop participants suggested a variety of projects directed toward the general goal of increased sophistication in human-modeling systems. Several ideas for integrating such simulations more directly with engineering data and the product development process as a whole were discussed. Some additional suggestions, such as animating task scenarios directly from natural language descriptions, offer intriguing research projects for future human-modeling systems, but do not specifically address the maintenance task/planning issue, that is, the extraction of maintenance action sequences.

As simulation analysis becomes more proceduralized and relies less on human observation, possibilities for directly passing task "critiques" back to engineering or task "descriptions" forward to aid the authoring process can begin to be pursued. Automated planning will play a significant role in the anticipated progression from human control and analysis of task animations to their construction and evaluation by machine.

Short Term

- *Visual Extensions*

  Pursue the inclusion and use of visual factors in simulations, such as where the technician looks and what he sees. Incorporate visual cues with the automatic generation of lighting and shadows (radiosity). Visual planning languages could potentially serve as the user interface.

- *Language Investigation*

  Begin construction of a "standard verb list" for encoding of animation actions. Analyze existing TOs for language content and descriptive style.

Medium Term

- *Biomechanical Enhancements*

  Develop a complete, biomechanically accurate model, including (a) sophisticated strength models for the whole body, (b) smooth real-time response, (c) collision avoidance, and (d) dynamic joint constraints with acceleration factors.

- *Agent Customization*

  Build a behavior "library" and customize task performance to specific anthropometric data. Investigate technician skill levels as factors in task performance.

- *Language Database*

  Develop computational definitions of verbs and actions, including object context and use of adverbs. Begin definition of a large-scale world database; draw upon CAD data to generate actions from object connections.

Long Term

- *Knowledge Representation*

  Complete compilation of the task description "verb list." Extend the generation of natural language descriptions from simulation steps. Dynamically link actions to text descriptions (i.e., "learning" a new verb definition).

- *Cognitive Modeling*

  Develop profiles of technicians' general task approaches/strategies (e.g., "doer" vs. "thinker"). Associate skill level and body factors to task completion failures. Model the learning of skills and associated performance improvements.

- *Planning and Reasoning*

  Add technician access and egress planning. Augment equipment models with common-sense reasoning about gravity and basic physics. Automate the evaluation of alternative task execution (posture planning and movement optimizations).

Text Generation and Graphics Synthesis

The overall goal in technical authoring is increased automation. Augmenting human writers and illustrators with systems which generate maintenance instructions and synthesize equipment diagrams will provide enormous and immediate cost benefits and raise the degree of customization (e.g., different repair contexts, technician skill levels, etc.) practical. This subsection addresses the creation of textual instructions for diagnosis and repair procedures, supporting graphics, and general descriptive information, as well as their linkage through various forms of cross-referencing.

The potential for future automation in this area involves at least two related dimensions.

- Synthesis of text and graphics directly from the LSA database to be stored in an associated "view package" database for loading by the technician, prior to begin ning a maintenance task.

- Dynamic generation of appropriate technical instructions and illustrations during the maintenance task itself.

The latter dimension may be alternately viewed as blurring the distinction between "authoring" and "presentation," or as promoting the authoring task to a meta-level. That is, rather than performing this task, the (meta-)author would specify (in software) how maintenance instructions should be generated from product knowledge.

The COordinated Multimedia Explanation Testbed (COMET) system, demonstrated at the workshop, is one example of current research work in this area (Feiner & McKeown, 1990). COMET uses a hierarchical knowledge base of components and repair procedures to dynamically plan the information content of each display (McKeown et al., 1991). It then selects and generates appropriate text and graphics explanation segments. Bringing systems like COMET out of the research laboratory and into the technician's PMA will require more direct use of product information, more sophisticated planning components, and further advances in display layout and user interaction.

As equipment becomes more complex and maintenance instruction more specialized, formal methods for establishing the correctness of both information content and presentation assume a greater role. The electronic manuals of the future will not only be interactive, but also highly dynamic and capable of supporting a wide range of possible maintenance scenarios. The large number of potential repair contexts and distinct presentations to suit them makes manual validation (i.e., working through every possible scenario by hand) infeasible. Automated verification systems must begin to take over verification/validation responsibilities in this area.

In step with the expected automation of authoring, the focus of verification technology will likewise shift from the technical information itself to the automated processes which produce it. The desired certification will likely depend upon establishing both correctness-preserving properties of the generation processes, and consistency requirements within the PKB and other knowledge sources.

The subsections below collect proposed generation and synthesis goals according to their respective identification with either procedural or general descriptive information. As noted earlier, diagnostic information was not a focus of the workshops.

Procedural Information

The stepwise detailing of repair and test procedures is action-oriented information, which, when "processed" by the technician, effects changes in equipment status. The implied dynamic effects of presenting such information must be modeled within the generation system.

Short Term

- *Stepwise Decomposition*

  Develop techniques for drawing task decompositions from the human-modeling simulation database. Use timing, position, and posture information to identify natural task breakpoints.

- *Plan Annotation*

  Use maintenance planning output (a plan data structure) from the logistics analysis as a structural "template" for annotation by a human expert. Build workstation-like tools to support the user in filling out this template with English text.

- *Behavioral Certification*

  Formulate logical assertions regarding stepwise presentation of tasks, satisfaction of preconditions, handling of follow-on conditions, and so forth within a "populated" Interactive Electronic Technical Manual (IETM) database. Build a corresponding reactive model and use an inference engine to certify correct behavior by proving satisfaction of these assertions.

Medium Term

- *Causality and Conditionals*

  Represent causality and effects relationships within the maintenance task database. Generate input conditions, post-conditions, and follow-on conditions from higher-level connections.

- *Coordination Constraints*

  Incorporate interacting constraints between generators for different media (e.g., text and graphics) which enforce correspondence in the underlying structure (e.g., three simple sentences related to three subdiagrams).

- *Temporal Media*

  Explore authoring for alternative time-ordered media such as animation and speech. Model temporal relations within the content planner for generation and synthesis to manage phrasing, delay, and so forth.

Long Term

- *Plan-Based Synthesis*

  Generate textual instructions directly from plan data structure(s). Determine whether sufficient information is present to support this.

- *Stylistic Variations*

  Support a variety of style conventions within text and illustration generators. Select and alter them based on display hardware profiles, human factors guidelines, and user preferences.

- *Verified Transformations*

  Formally establish "correctness-preserving" properties of the generation and synthesis systems used to automate the production of text and graphics from LSA sources.

Descriptive Information

Technical data not specific to a particular maintenance procedure (e.g., operational explanations, generic illustrations, and various forms of cross-referencing) fall in the category of descriptive information. Since the intended usage will be less predetermined than that of procedural information, the content will be more dynamic.

Short Term

- *Simple Animations*

  Animate two-dimensional illustrations of component modules and indicate the data flow along interconnections. Develop standard mechanisms to render and/or highlight individual components based on their current fault classification.

Medium Term

- *Design-Based Illustration*

  Generate 3D equipment illustrations from engineering CAD models. Support exploded views, and include cross-references to textual operation descriptions.

Long Term

- *Complex Animations*

  Generate 3D animations from design models and qualitative physics information. Show internal details and mechanical interaction. Provide "cut-away" illustrations, interactive zooming, view rotations, and other alternative viewpoints.

Dynamic Presentation and Virtual Reality

Maintenance presentation covers the actual delivery of information to the technician during a given maintenance task. This delivery must be dynamically driven by the related tasks of diagnosing and resolving problems. In the near term, this information will consist of a sequence of interactive electronic displays appearing on the technician's PMA. The screens presented during a given maintenance scenario will vary greatly with the technician's actions and the ongoing repair.

As generation and synthesis tools become more advanced, and PMAs become more powerful, less of the text and graphics which make up each screen is likely to be "canned" (i.e. authored and stored within a previously loaded view package) and more is likely to be generated dynamically. A subset of the PKB, along with the generation software, could be loaded and carried within the PMA, rather than a (fixed) number of precomposed screens.

As the displays become more sophisticated and the presentations more dynamic, the notion of individual (discrete) screens will fade; a VR presentation appears continuous. As discussed in the previous section, the possibility of generating text and graphics "on the fly" (i.e., from a knowledge base of maintenance plans, engineering data, and so forth) effectively shifts the current distinction between authoring and presentation up a level of abstraction and control. Thus, the writers write parts of the generation software.

The advent of VR systems will drastically change the current conception of electronic information and how it is displayed. Hardware and software advances in this realm are rapidly increasing the potential for the practical application of VR to a wide range of information delivery requirements. It was claimed during the workshop that within ten years, VR capabilities greatly exceeding those available today could be supplied through lightweight electronic "glasses" and a "belt-pack" computer.

Managing the vast databases of drawing and behavior detail required is a significant issue for VR-based presentation. The engineering design information stored within the PKB could be used more or less directly by the VR software to generate the detail necessary for realistic equipment illustrations as overlays or perhaps exploded views. However, a VR presentation would be even more dynamic, with an effectively infinite number of possible "scenarios," than those anticipated for the coming generation of PMAs. Automated means for checking and certifying such presentations or, more directly, the generation software, will be even more necessary.

The first subsection below addresses identifying and solving problems. The second subsection completes the loop of passing maintenance experiences in the field back to LSA and, ultimately, engineering design.

Troubleshooting, Replacement, and Repair

The basic thrust of advances in troubleshooting, replacement and repair is toward increasing the technician's information sources through multimedia representations of equipment state and potential problems. A wide variety of correlations between components' physical characteristics and possible depictions could be explored. Temperature shown as color and current depicted via tone frequency are some obvious correlations. Human pattern-matching skills are very good; therefore, the technician might recognize, through such depictions, some mechanical behavior difficult to capture algorithmically.

The technician's physical relation to the aircraft is of more concern in this area than the others because subassemblies may be unexpectedly difficult to access. Any "contortions" required of the technician will be harder to describe than equipment details. Animations from human-modeling could be played back on a high-resolution PMA screen. Ironically, dependence on the PMA can limit the technician's agility. That is, holding or viewing a typical (even small) portable "computer with display" may be difficult during some tasks. A VR headset would be more flexible in such cases.

Short Term

- *Selective Scaling*

  Begin development of selective scaling. Investigate highlight and zoom mechanisms (e.g., cams, cones, abstractions, fish-eye views, etc.) for functional diagrams and wiring schematics. Support selective emphases according to current fault/symptom states.

- *Plan Execution*

  Implement a prototype plan execution system within the PMA. The plan would come from LSA, with English annotations, and be highly conditional. Early technician acceptance is critical.

Medium Term

- *Audio Output*

  Investigate ways to utilize audio output as a diagnostic aid, such as listening to the current draw of a solenoid through an earphone for which characteristic tone changes indicate impending failure.

- *History Visualization*

  Construct visual representations of component performance history (e.g., graph, bar chart, color coding, etc.) for potential diagnosis by the technician.

- *Virtual Overlays*

  Provide VR capabilities for highlighting suspected components or subsystems as overlays viewed within a "heads-up" display. Offer these capabilities across the whole (or most of) a selected vehicle/system.

- *VR Toolkit*

  Support technician selection of specific, modular VR capabilities and/or equipment visualization data structures (sub-"worlds") as "tools" for a particular repair task.

- *Dynamic Replanning*

  Provide a limited PMA replanning capability making (probable) use of temporal logic. Determine if this is a desired capability.

Long Term

- *Behavior Animations*

  Develop VR animations simulating behavior and technician observation of equipment with various possible problems. Generate the animations dynamically from test results and equipment self-monitoring information.

- *Subassembly Detailing*

  Generate holographic or VR depictions of individual component fit, access, assembly, and disassembly within complex mechanical substructures. Investigate uses of color, animation, rotations, alternate view points, and so forth.

Capture and Review

A variety of new knowledge may be gained during the actual execution of a given maintenance activity. The recording and linking of this knowledge back into LSA processes for review offers an additional dimension for maintenance support analyses.

Short Term

- *History Replay*

  Replay maintenance session history to check for inconsistencies and compare with statistical projections and certification results.

Medium Term

- *Decision Support Feedback*

  Record equipment failure rates and maintenance operation problems within the PMA for uploading back to LSA decision-support components. Attempt to facilitate better decision-making in the future.

Long Term

- *VR Recording*

  Record actual repair operations performed by the technician through a "data-glove." Investigate use of a full VR "body-suit" for task recording. Evaluate whether this is too awkward and/or constricting. Compare the results with human-modeling simulations for modification and re-analysis.

V. CONCLUSIONS AND REVIEW

PMAs, sophisticated task animations, and the possibility of automatically generating instructional text and illustrations were unknown 13 years ago when the "Sgt. Bayshore" scenario was written. The coming decade holds a similar promise for VR, comprehensive and accessible product databases, and expert system and domain-specific planning capabilities expected to become practically available. To realize that promise, similar plans for extending and integrating these emerging technologies must be formulated now.

As the first step towards developing such a plan, AL/HRG hosted a workshop in Palo Alto which brought together a number of experts to discuss current and future work in various applicable fields.

Key Themes

Several primary themes for a future focus emerged from the first workshop:

• **Comprehensive Product Information**—All design, engineering, and logistics information must be kept in a common PKB throughout a system's or component's effective life cycle. Information should be stored and maintained in accordance with standard organizing principles, and be supported with standard mechanisms for extraction and review across a wide range of potential users, both human and machine.

• **Automated Generation of TOs**—Automated synthesis tools can begin to augment, and eventually replace, human writers and illustrators. The "authoring" task should become one of applying and tailoring these tools to produce the desired output.

• **Formal Certification Methods**—Traditional "validation and verification" procedures must be supplanted by automated certification tools. Both the depth of technical information and variability of its presentation will make manual checking of consistency and correctness infeasible.

• **New Presentation Capabilities**—Electronic presentation of text and graphics on a PMA will seem primitive compared to the coming possibilities for information delivery. The hardware for supplying virtual overlays on a head-mounted visor (for instance) or sophisticated 3D animations is imminent. The software for extracting the necessary engineering detail to utilize this potential should be developed now.

• **Design Concurrency**—Technology must be developed for controlling and implementing design and/or operational changes from the CAD/CAE workstation, through technical data generation, to delivery in the field. This is fundamentally a Computer Aided Logistics Support (CALS) issue. Accuracy and currency of technical data must be assured, no matter how it is delivered, because systems are constantly being reconfigured or re-engineered.

VI. RESEARCH RECOMMENDATIONS

The first workshop laid the groundwork for developing future maintenance support capabilities and identified the primary research directions and key technologies to be pursued. The second workshop refined this focus and defined an initial set of capabilities upon which work could potentially begin.

The subset of original participants who reconvened at AL/HRG in March 1992 were instructed to narrow their focus considerably in order to agree on a specific research agenda for prospective funding. Accordingly, the panel decided to concentrate on the mid-phase processes of LSA and Technical Authoring. These activities, particularly the creation and validation of technical data, have traditionally been the most expensive in terms of human resources.

The group's working premise was that various forms of product information would be available from engineering phases and, similarly, various electronic presentation capabilities would be developed for information delivery. Focusing on the middle phases of LSA/authoring would help to better define both the specific product data required from engineering and the general structure of the resulting maintenance task information.

Within this restricted scope, a number of individual subprocesses were identified. The panel agreed that it was essential to compose an integrated collection of prototype tools that would cut across more than one maintenance (sub-)product phase. The suggested high-level approach was to select one or more relatively simple components (such as a pump or radar display) to provide a point-to-point focus for the individual projects. This concentration would facilitate demonstration of the passing forward (and back) of information between different activities, again recognized as a cornerstone of the planned advances.

Architectural Design

To provide a skeletal framework for researchers developing individual tools, the group made several high-level architectural design decisions. The accommodation and integration of diverse technical information, expressed within a variety of representations, and the potential for inconsistency and error which naturally accompanies such diversity, were the key points to be addressed.

The stepwise planning and detailing of aircraft maintenance tasks involve a number of different, though interrelated, forms of information. Engineering geometry, human performance models, textual instructions, and graphic illustrations are primary examples of the distinct data domains which must somehow be coordinated to maintain overall consistency and correspondence.

Since maintenance *plans* are both the foremost product of LSA and the key element of support information, the group agreed that a planning language representation should provide the core knowledge formulation and structural foundation for the maintenance knowledge base. Engineering geometry, performance models, text, illustrations, and other forms of information will be attached to and organized within the internal plan data structures. Conceptually surrounding this plan-based core are a number of relatively independent tools which provide services such as extraction, explanation, and consistency checking, specific to the other information domains. Figure 4 illustrates the basic functional architecture and introduces the principal tools to be developed.

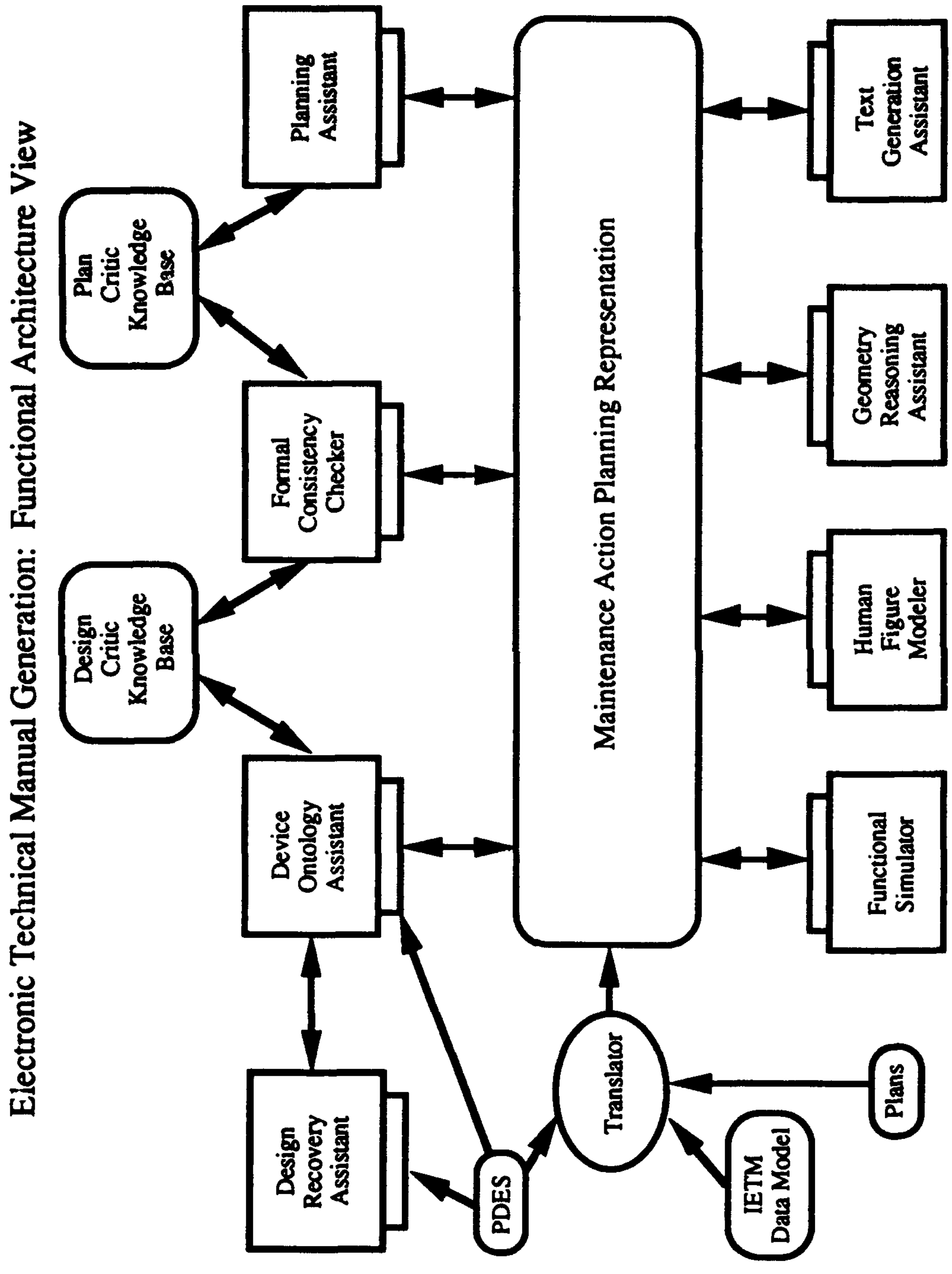

Figure 4
Proposed Functional Architecture and Principal Tools

Planning Language Foundation

A uniform plan representation is central to the design of the maintenance information knowledge base. Figure 5 shows a basic AI-planning view of the TO generation process.

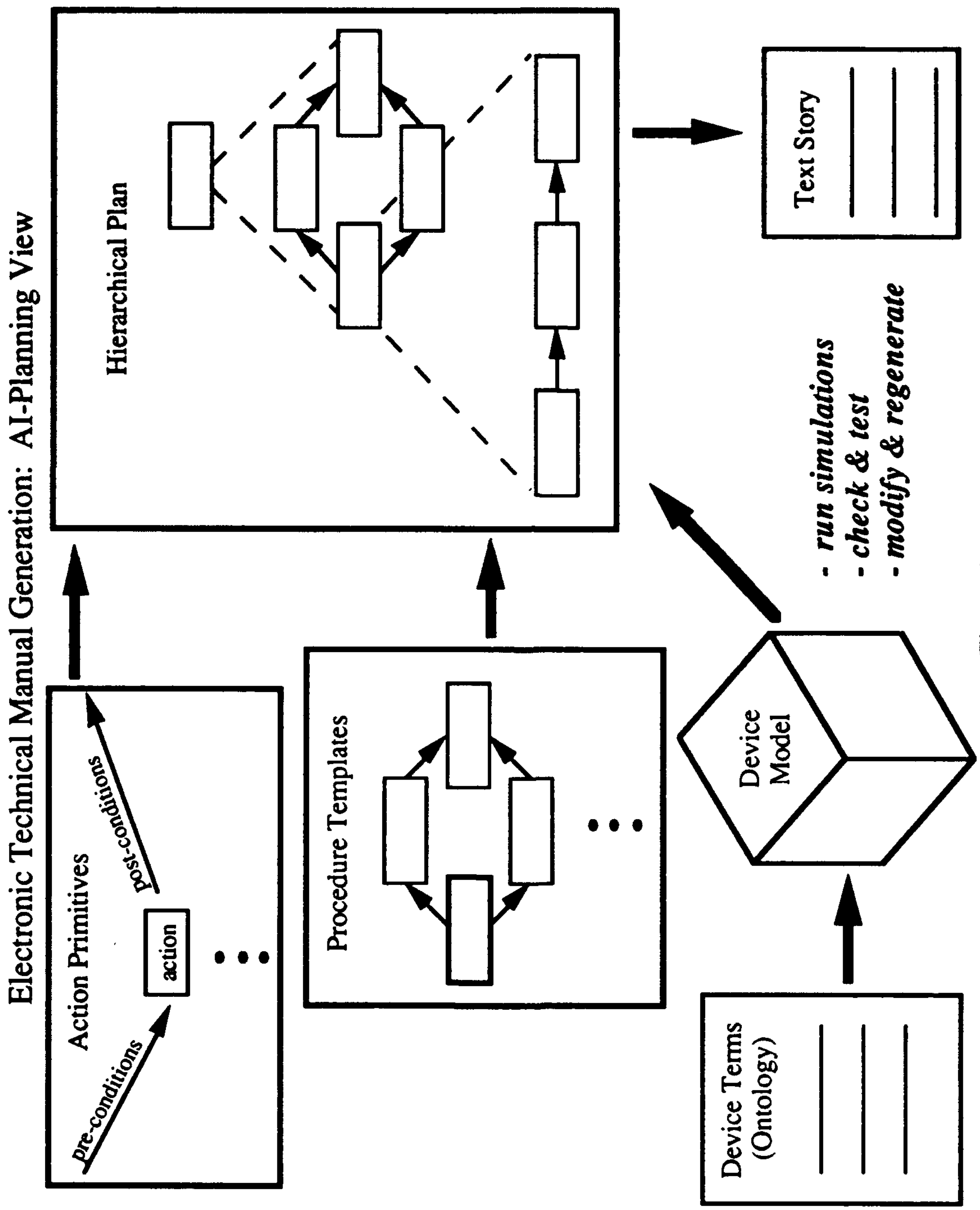

Figure 5
Plan-Based View of Automated Technical Manual Creation

The planning language selected (or developed) should be hierarchical in order to permit incremental decomposition in accordance with aircraft system and component hierarchies, and down through individual maintenance task steps. As the foundation for the wide range of technical information anticipated, the planning language must be flexible and extensible. It must accommodate the variety of supporting data currently identified as well as those to be developed in the future.

The various forms of additional information will presumably be stored within the database through a corresponding variety of annotations to the basic plan structure. Further annotations could state dependency relationships, specify constraints to be maintained, and/or assert conditions expected to hold among these annotations. Thus, the planning language base should further support notational facilities for expressing such connections and inference mechanisms for reasoning about them.

The central role of the planning language dictates that one language be settled upon as soon as possible, since design of all the other tools will depend on (at least) its high-level structure. This, in turn, suggests that an existing language which best satisfies the criteria above should be chosen, rather than designed and developed from scratch, thus forcing the delay of significant work on other tools until its details emerge. The Reacto specification language and verification system was discussed by the group as an example of the kind of extensible foundation sought (Gilham et al., 1989).

The Reacto language, designed for the specification and verification of complex reactive systems, is formally based on the model of hierarchical finite state machines or *State-Charts* (Harel, 1987). A state-chart specification may be viewed as corresponding to a plan in which the universe of possible state descriptions has been recursively partitioned into a tree of state classifications. Reacto's existing graphic interface for specification acquisition, automated verification capabilities, and interactive simulation facilities could be enhanced and/or modified to similar LSA and maintenance information requirements.

Some other AI-based planning systems were also mentioned as potential candidates. The Noah system has been applied to the planning of a pump overhaul task (Sacerdoti, 1975) and the O-Plan project has addressed some aspects of interactive plan animation (Currie & Tate, 1991). A careful comparison of the inherent advantages and potential problems of existing candidates must be made, as well as their likely ease of adoption. The system selected will exert considerable influence on the research and development of automated translation tools, design critics, and domain-specific assistants which collectively serve the planning domain and its various subordinates.

Translators, Critics, and Assistants

As introduced above, technical information from other data domains will also be incorporated within the overall maintenance plan hierarchy. Though some functional overlap may be expected and hoped for, in terms of an architectural overview, it is simplest to assume that each such domain (e.g., engineering geometry, human models, text, graphics, etc.) will be supported by separate and independent tools constructed specifically to serve the associated information type.

Nonetheless, the individual tools may be viewed as sharing several basic operational forms, in addition to their common knowledge concerning both the high-level structure of plans and whatever standard protocol exists for communicating with the plan database. In general, each domain will require facilities to support: (a) storage and retrieval, (b) evaluation and consistency checking, and (c) user- and/or author-directed modification of technical data within the given domain. Accordingly, the tools to be developed may be categorized with respect to their basic function as "translator," "critic," or "assistant."

Translation tools support information flow across database boundaries, by bridging the gap between plan data structures and the alternative representations specific to the other domains. This "translation" may in some cases simply be the accessing of a particular annotation, such as an illustration accompanying a task step. Other cases may involve significant analysis and processing, such as the incorporation or extraction of numerical data relating physical exertion and expected task performance time.

Domain-specific "critics" judge and report on the relative "goodness" of database information. Consistency checking and maintenance is the most important category for such evaluation, but there are other possible categories as well. For example, illustrations can be graded as more or less cluttered and instructions as more or less readable independent of the degree to which they concur with other technical data.

The potential autonomy of such tools covers a broad spectrum. At one end lie static search procedures and/or pattern-matchers, invoked by the user/analyst and given a specific condition to check for. A number of knowledge-base support systems provide this basic capability. At the other end, one may envision active agents which continuously monitor changes within the database for violation of interdependencies and functional constraints, infer the additional modifications required, and automatically perform them. Such agents have been implemented, for example, within the Project Management Assistant to address a wide range of complex (*condition*, *action*) pairs involving event characterizations, policy descriptions, and a variety of constraint formalisms (Qian et al., 1990).

The notion of domain "assistants" follows traditional usage of the term in suggesting (a) an integrated collection of high-level capabilities for user interaction, (b) some "understanding" of the domain's internal relationships, and (c) the automation of more or less mechanical subtasks (Green et al., 1993). As in other realms, the basic user task to be supported is the creation and incremental refinement of some formal description(s), in this case varieties of logistics information and maintenance task plans, along with instructions and illustrations for the technician. Layered on top of other interactive tools, the assistant will normally draw upon and may totally encompass the functionality outlined above.

Depending on the complexity of a given domain and the current degree to which its processes are formally understood and have been proceduralized, the assistant's contribution may range from simply improving user efficiency to assuming most of the attendant task. In text authoring, for example, interactive editors will eventually be supplanted by assistants which synthesize textual instructions directly from the maintenance plans, requiring only minimal guidance and little editing/review by the human "author."

While not all the tools proposed in the research agenda below fit neatly into these three categories (translator, critic, or assistant), many of them do. The exposition above hopefully offers some insight for uniform tool design.

Initial Agenda

The project items outlined below constitute an initial research agenda for the next one to two years. As noted above, the intention is to select a particular component or subassembly (such as a pump), and use it to help focus and connect potential advances across the typical phases of maintenance information support—from engineering design to presentation. The items below concentrate primarily on LSA/authoring processes, but other processes are addressed (to some extent) as well to emphasize and demonstrate at least minimal point-to-point connections.

(1) *Engineering Feature Extraction*

Extract several key engineering features from the product design for the selected component(s) and incorporate them within the planning knowledge base. This initial exercise in design recovery will be done largely by hand, but may also employ available translation capabilities (see Item 3) outlined below. The intent is to draw upon CAD and other (e.g., PDES) defining data to help identify the additional extraction and translation facilities required, and to begin to address the use of qualitative physics in logistics analysis.

(2) *Geometric Model Construction*

Construct one or more geometric models to support maintenance planning and simulation for the product(s) addressed. The models should link with existing DEPTH facilities and also be accessible through the planning representation developed as part of this agenda. As with Item 1, construction of specific models for the selected subassemblies will serve to expose the foundations for eventually automating such constructions and will help to focus future efforts in this area.

(3) *Prototype Translation Facilities*

Develop a preliminary set of facilities for translating engineering design descriptions into corresponding plan-based representations. These facilities should augment and be developed concurrently with the (mostly) manual extraction suggested in Item 1. Emerging PDES standards, current IETM data model specifications, and external plan formalisms are the principal domains to be considered.

(4) *Device Engineering Critic*

Design and implement an initial device engineering critic to address maintenance implications of product design. This component will access and analyze engineering data incorporated within the planning knowledge base, and draw upon its own engineering knowledge base to provide feedback to both maintenance task developers and product engineers. Such information might also be passed back to design processes directly, through translation (as in Item 3) to the appropriate engineering representation.

(5) *Basic Procedure Library*

Define the structure and organization of a basic maintenance procedure library. The structure of procedure descriptions and how they are indexed and classified must be established, using the planning representation as a base. The library must then be populated with 25 to 30 standard maintenance actions, using composition tools (such as Item 6) when possible. Serving as an extension of the planning knowledge base, such a library will be essential for procedure uniformity and reuse.

(6) *Procedure Assembler*

Develop an interactive tool for assembling and composing maintenance procedures from individual steps and/or subprocedures. The tool must support basic access and storage capabilities across the procedure library, as well as facilities for construction and modification of procedure descriptions, perhaps through the provision of procedure templates. In addition, the tool should help insure that hierarchical correspondence with the underlying maintenance plan be upheld and assist with simple forms of condition propagation and consistency checking between individual steps.

(7) *Procedure Critic*

Design and implement a preliminary procedure critic to analyze and evaluate descriptions within the library. Together with Item 6, this will provide a foundation for developing an integrated procedure assistant. Procedure principles to be addressed include basic structural requirements, precondition achievement, potential policy violations, pre- and post-condition matching, optimization, and causality effects.

(8) *Planning Assistant*

Explore the potential for procedure synthesis, through the development of a prototype planning assistant. Though potentially expensive, successful implementation of such an agent would provide a very high payoff, and largely subsume Items 6 and 7. The idea is to approach procedure construction and evaluation from a higher-level planning viewpoint, employing such notions as resource minimization, optimization, generalization, and plan reuse. Explicit maintenance procedure descriptions would be generated automatically from the annotated plans.

(9) *Text Generation Assistant*

Apply and extend current capabilities for automated text generation within a (more comprehensive) text generation assistant. The basic synthesis approach will employ templates corresponding to the given procedure decomposition and standard word lists. Initial output may be somewhat stilted but will improve with the incorporation of human factors constraints. As with Item 6, the templates should be linked to the appropriate elements of the plan representation to facilitate evaluation and consistency checking.

(10) ***Layout Assistant***

Develop a layout assistant to combine text, tables, and graphics within technical presentations. The presumed capabilities (previously demonstrated) include extraction and scaling of equipment illustrations from engineering (CAD) drawings, synthesis of simple block diagrams from functional abstractions, and generation of tables from relational data. Stylistic variations and structural/stepwise correspondence between text and related graphics should also be supported.

(11) ***Screen Structure Critic***

Design and implement a prototype critic for the presentation of maintenance instructions as distinct PMA screen displays. This is a first step towards automating the final QA process, currently performed by humans. One initial approach would be to develop a set of metrics for screen structure and layout, and use them to tag questionable displays for human review. Since these electronic "pages" potentially vary with the presentation hardware, as do guidelines for complexity with technician skill levels, the design should anticipate parameterization of the evaluation metrics.

(12) ***Consistency Checking Engine***

Begin to identify and collect the inference and analysis mechanisms (used by various "critic" agents) into a generic consistency checking engine. Issues to be addressed include correspondence between plans and procedures, resource and time constraints, test information, configuration management, change propagation, and version control. The idea is to eventually provide a general-purpose automated reasoning server to support the particular analyses required across the various domains.

(13) ***Procedure Interpreter/Animator***

Implement a basic facility for interpreting maintenance procedure descriptions and animating their performance by a technician. Much of the necessary human-modeling and graphics technology for this currently exists in systems such as Jack, Crew Chief, and DEPTH. Thus, the task is to select an appropriate subset and augment or modify it to use the central planning representation and associated procedure descriptions, as required.

(14) ***Integrated User Interface***

Integrate the tools and capabilities outlined above within a supporting framework for (graphical) user interaction. This amounts to a working prototype of the envisioned author's workstation. Individual windows will display both static and dynamic views, corresponding to the different representation domains, of the maintenance procedure under construction. Figure 6 illustrates the concept, showing a plan view, a text view, a presentation system view, and a task animation view. Intended to be a relatively low-cost item, this demonstration prototype will nonetheless be important for obtaining early user feedback and achieving overall program acceptance.

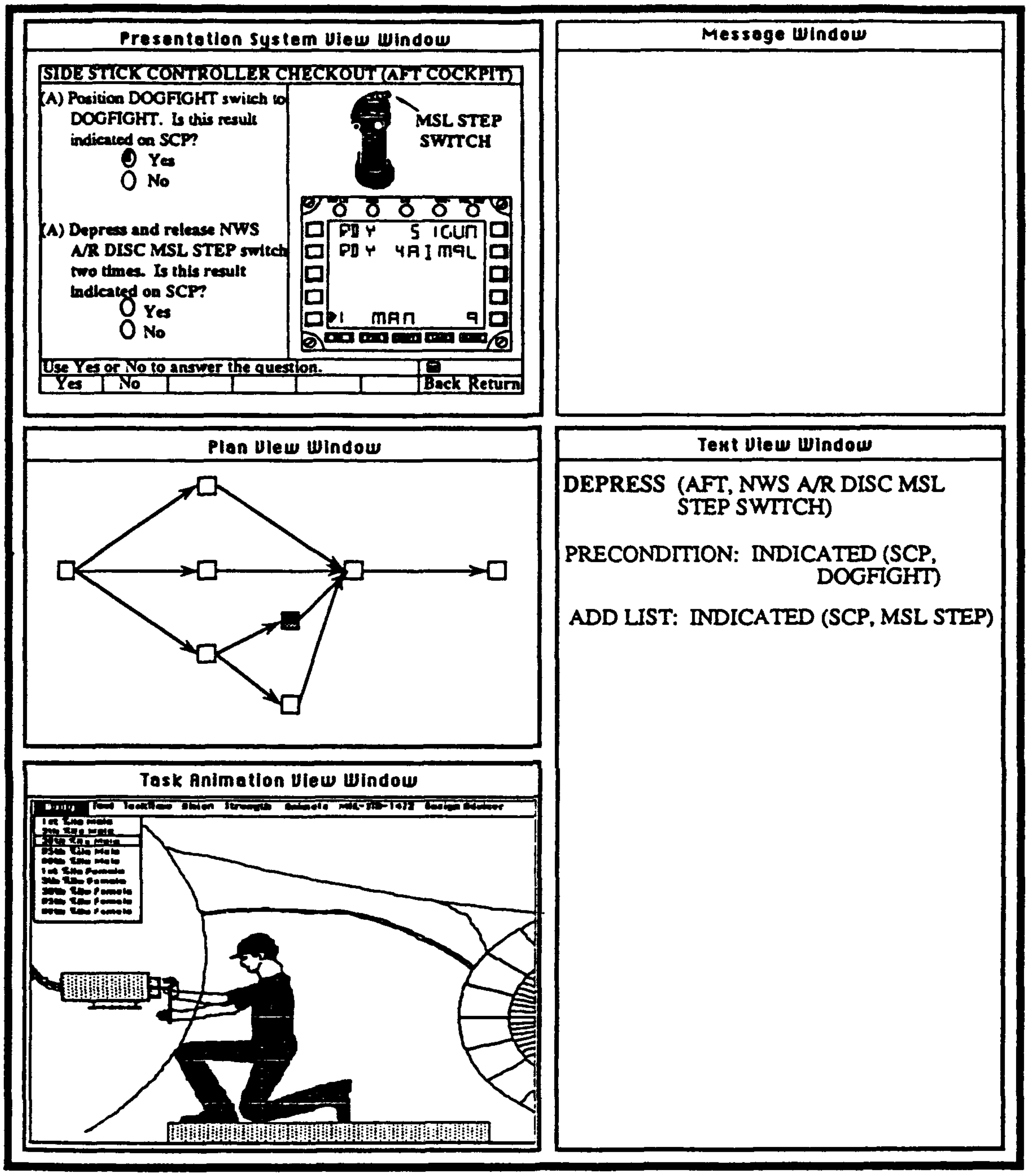

Figure 6
Integrated Graphical User Interface—Author's Workstation Concept

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WORKSHOP PARTICIPANTS

Norman Badler

Norman I. Badler is the Cecilia Fitler Moore Professor and Chair of Computer and Information Science at the University of Pennsylvania. He has been a faculty member since 1974. Active in computer graphics since 1968, his research focuses on human figure-modeling, manipulation, and animation. Dr. Badler received a B.A. degree in Creative Studies Mathematics from the University of California at Santa Barbara in 1970, an M.Sc. in Mathematics in 1971, and a Ph.D. in Computer Science in 1975 from the University of Toronto. He is co-editor of the Journal of Graphical Models and Image Processing. He also directs the Computer Graphics Laboratory with three full-time staff members and about 40 students.

Edward Boyle

Edward Boyle is a Research Psychologist at the Air Force Armstrong Laboratory, and Program Manager of Project DEPTH (Design Evaluation for Personnel, Training, and Human Factors). DEPTH is a maintainability evaluation tool based on computer aided design (CAD) which features computer graphics human-figure models. Mr. Boyle has a great deal of experience with Air Force manpower, personnel, and training analysis for acquisition. He received his M.A. in Psychology and M.B.A. in Management from the University of Dayton.

George Brown

George W. Brown is a Senior Staff Specialist with the Automatic Test Systems focused business unit of General Dynamics Electronics Systems, Inc. He is the principal software architect for the Integrated Maintenance Information System (IMIS) project , and has over 25 years of experience in software development, with consistent focus on interactive computing. In the last six years, his principal interests have been in cooperative processing in distributed workstation environments and the use of object-oriented methodology for analysis, design, and implementation on projects ranging from battle management to maintenance information systems. Mr. Brown holds BSAE and MSAE degrees from Georgia Tech.

Johan deKleer

Johan deKleer is manager of the Systems and Practices Laboratory of Xerox Corporation's Palo Alto Research Center. He studied at the Massachusetts Institute of Technology Artificial Intelligence Laboratory and received the Ph.D. degree from that institution in 1979. He has been working on truth maintenance systems since their inception. His paper on that topic in AAAI-84 shared the publisher's prize. His central research goal is developing computational theories of reasoning about complex physical artifacts. His main research interests include problem-solving, truth maintenance systems, qualitative physics, and diagnosis. Dr. deKleer has published widely in all these areas and has received the

Computers and Thought Award at IJCAI-87 for his research contributions to artificial intelligence (AI).

Mark Drummond

Mark Drummond received a B.Sc. in Computer Science from the University of Calgary in 1982 and a Ph.D. in AI from the University of Edinburgh in 1987. He worked for two years at the AI Applications Institute in Edinburgh as a consultant on planning and scheduling for various European companies and government organizations. Dr. Drummond is currently employed by Sterling Software, and works at the National Aeronautics and Space Administration Ames Research Center. His general research interests include temporal and spatial reasoning, real-time systems, scheduling, and decision support systems. Dr. Drummond is leader of the Entropy Reduction Engine project, the focus of which is the integration of techniques from AI-planning, scheduling, and discrete event control. Dr. Drummond is the author of over 15 publications in the areas of planning and scheduling.

Steven Feiner

Steven Feiner is an Associate Professor of Computer Science at Columbia University. He received a Ph.D. in Computer Science from Brown University. His research interests include knowledge-based design of graphics, user interfaces, virtual worlds, animation, visual languages, image synthesis, hypermedia, and visualization. Dr. Feiner is on the editorial board of Electronic Publishing, is an Associate Editor of the Association for Computing Machinery (ACM) Transactions on Information Systems, and is co-author of Computer Graphics: Principles and Practice. He is program committee co-chair for ACM Multimedia '93, and co-chair of the 1993 Institute of Electrical and Electronic Engineers (IEEE) Symposium on Research Frontiers in Virtual Reality (VR). In 1991, Dr. Feiner received an Office of Naval Research Young Investigator Award.

Allen Goldberg

Allen Goldberg received his M.S. in 1974 and his Ph.D. in 1979, both from Courant Institute in Computer Science. He received a B.S. in Mathematics from State University of New York, Stony Brook, in 1972 . The title of his Ph.D. thesis was ``On the Complexity of the Satisfiability Problem." His interests include high-level program optimization, transformational programming, programming language theory, and computational complexity. Dr. Goldberg is currently working with Kestrel Institute on the development of knowledge-based tools for algorithm design and high-level program optimization. He also supervises students studying at Kestrel.

Cordell Green

Cordell Green is Director and Chief Scientist of Kestrel Institute. Dr. Green's research interests center on knowledge-based tools for software engineering. He has worked on systems that help automate acquisition, analysis, and synthesis of software as well as in the area of foundations of logic programming. His recent interests have been in automated algorithm design, synthesis of visual representations of software, software engineering, and formal methods in testing. Dr. Green is a member of the editorial board of the Journal of

Automated Reasoning and is an editorial advisor to the Journal of Logic Programming. He was presented the Grace Murray Hopper Award by the ACM in 1985. He received the award for establishing a theoretical basis for the field of logic programming. He has served as a member of the Air Force Studies board, during which time he took part in a study concerning methods of improving software quality and life-cycle cost. Dr. Green received a B.A. and B.S. from Rice University in 1963 and 1964, respectively. He received his M.S. in 1965 and Ph.D. in 1969, both from Stanford University, in Electrical Engineering.

David Gunning

Dave Gunning is a Research Psychologist and Computer Scientist in the Logistics Research Division of the Human Resources Directorate at Armstrong Laboratory. He provides technical direction for the development of IMIS and has spent the last eleven years developing and field testing electronic maintenance information systems. In 1984, he developed and field tested one of the first automated technical manual systems in the Department of Defense (DoD). He is also a key contributor to the DoD's Computer-Aided Acquisition and Logistics Support (CALS) program and is a co-author of Dod's specifications for Interactive Electronic Technical Manuals (IETMs). Mr. Gunning holds an M.S. in Computer Science from Stanford University and an M.A. in Psychology from the University of Dayton.

Jaron Lanier

Jaron Zepel Lanier is a computer scientist specializing in programming language design and virtual reality systems. He is one of the pioneers of visual programming languages. He is also one of the founders of the field of VR and was the first to coin the term. Mr. Lanier and the team he assembled at VPL Research, Inc., have been responsible for many of the central innovations in the field, including glove input devices and networked head-mounted display systems. Mr. Lanier founded VPL Research, the first company to bring virtual reality products to the marketplace.

Peter Wilson

Peter R. Wilson's research interests lie in the area of information modeling, which is a new technology providing a higher level of abstraction than traditional data modeling. He is currently a Senior Research Associate at Rensselaer Polytechnic Institute and has previously worked in computer-aided design and manufacturing (CAD/CAM), solid modeling, and semiconductor physics for organizations such as the General Electric Research and Development Center, and the Lucas Research Centre in the United Kingdom. He has published many papers on the mathematics of semiconductors, CAD/CAM, and product data exchange standards, and was a principal developer of the solids portions of the Interim Graphics Exchange Standard (IGES) and the Standard for the Exchange of Product Data I (STEP). In 1991, he was appointed Editor in Chief of IEEE Computer Graphics & Applications.

Gary Worrall

Gary Worrall worked as a computer research scientist at the Air Force Armstrong Laboratory from 1990 to 1992, directing research on the development and use of systems to author IETM data for Air Force weapon systems. He received a B.S. in Computer Science from the University of South Florida in 1984 and an M.S. from the Air Force Institute of Technology. Gary currently works for the IBM corporation in Rockville, Maryland, developing Ada software for the Initial Sector Suite System, which is part of the Federal Aviation Administration's Advanced Automated System.

David Zimmerman

David L. Zimmerman received B.S. degrees in Mathematics and Computer Science from Purdue University before joining the Lawrence Livermore National Laboratory in 1980 as a Computer Scientist, and beginning graduate work within the Laboratory's Department of Applied Science. He received a Master's Degree in Computer Science from the University of California at Davis/Livermore in 1982, and his Ph.D. in 1988. Dr. Zimmerman's early work has been in the design and implementation of programming languages and programming support systems. Since coming to Kestrel Institute, he has worked on the synthesis of graphical displays, reactive system modeling and verification, and formal approaches to software testing.

ACRONYMS

		Page
3D	Three Dimensional	2
ACM	Association for Computing Machinery	44
AI	Artificial Intelligence	2
AL/HRG	Armstrong Laboratory, Logistics Research Division	1
CAD	Computer-Aided Design	2
CAE	Computer-Aided Engineering	30
CALS	Computer-Aided Acquisition and Logistics Support	30
CAM	Computer-Aided Manufacturing	18
COMET	COordinated Multimedia Explanation Testbed	24
DEPTH	Design Evaluation for Personnel, Training, and Equipment	9
DoD	Department of Defense	3
IEEE	Institute of Electrical and Electronic Engineers	44
IETM	Interactive Electronic Technical Manual	1
IGES	Interim Graphics Exchange Standard	2
ILS	Integrated Logistics Support	9
IMIS	Integrated Maintenance Information System	9
LSA	Logistics Support Analysis	1
NAC	National Airplane Company	3
NASA	National Aeronautics and Space Administration	17
OFP	Operational Flight Program	16
PDES	Product Data Exchange using Step	14
PKB	Product Knowledge Base	18
PMA	Portable Maintenance Aid	2
QA	Quality Assurance	2
STEP	Standard for The Exchange of Product data	14

TO	Technical Order	7
VR	Virtual Reality	2

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