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MODERN COMPUTER-AIDED TOOLS FOR HIGH-RESOLUTION WEAPONS SYSTEM ENGINEERING

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FEBRUARY 1988

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY

ABERDEEN PROVING GROUND, MARYLAND

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It is generally recognized that the potential to design and build better materiel is intimately connected with the capability to apply the evolving techniques of computer analysis and automation. At the outset of the cycle from concept to manufactured product, the techniques of Computer-Aided Engineering (CAE) provide the crucial capability to exercise predictive analyses of performance before systems are built. It is in the engineering phase of materiel development that optimum system designs can be generated, if properly supported via CAE.

In order to fulfill its role in Army Materiel Command (AMC) as the lead laboratory in Vulnerability/Survivability, the Ballistic Research Laboratory (BRL) has developed a broad set of CAE tools that are appropriate to the examination of armored fighting vehicles, aircraft, and other military systems.

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The keystone of these predictive engineering models is a unified geometric modeler in which three-dimensional geometry is linked to material specification. All subsequent engineering analyses derive from a single geometric model. When highly detailed three-dimensional geometry is combined with phenomenologically based predictive models, it becomes possible to perform high-resolution estimates of weapons system performance.

In this paper, an overview of such tools is presented, with examples. In addition, supporting issues of computer operating systems, electronic networking, the transfer and sharing of geometric data, and the retargeting of code to new hardware architectures are discussed.

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I. INTRODUCTION

Computer automation is being applied to the complete life-cycle of materiel development from concept to manufacturing and even beyond. In the Army, the Office of Manufacturing Technology at Army Materiel Command (AMC) is responsible for supporting the technologies associated with Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM). Primarily for historical reasons, the major area of attention has been in CAM. The result has been a substantial improvement in manufacturing quality, cost, and productivity. By contrast, the concepts of Computer-Aided Engineering (CAE) have seen far less exploitation throughout AMC. Based on the relative monetary costs involved in manufacturing vis-a-vis R & D, the attention given to CAM is merited. However, the techniques of CAE provide the crucial capability to exercise *predictive analyses* of performance *before* systems are built when designs can be changed with little relative expense. It is in the engineering phase of materiel development that *optimum* system designs can be generated if properly supported via CAE.

In order to fulfill its role in AMC as the lead laboratory in Vulnerability/Survivability, the BRL has developed a broad set of CAE tools that are appropriate to the examination of armored fighting vehicles, aircraft, and other military systems. This set of tools has been developed within, and is supported by, a powerful, general-purpose computing environment. It is the aim of this paper to discuss the underlying philosophies and objectives that have influenced the development of that environment. Below we will attempt to enunciate in broad terms the requirements for a CAE environment, starting with a top down view. Next, we will examine how modern computer hardware and software is used to construct what is known as an operating system (OS). With this background, the course BRL has taken to bring together enhancements to that environment and the development of specialized CAE tools will be discussed. Finally, examples of particular tools, geometric modeling, and system analyses will be illustrated.

II. REQUIREMENTS FOR CAE

The goal is to establish a capability with which detailed analyses of weapons systems can be performed. As we shall see later, these analyses can be quite eclectic, ranging from the more familiar mechanical design tasks through armor penetration studies to optical signatures. We emphasize this requirement since it has been our observation that typically CAD has tended to imply a comparatively narrow area of mechanical analysis in which system parts, for example, are designed and examined for particular mechanical properties. The more general requirement entails the examination of very large systems (such as armored fighting vehicles and aircraft) with, as noted above, a large collection of analysis tools for assessing how specific designs *quantitatively* fulfill mission roles.

We start our look at the requirements for a CAE environment from the top down. As discussed previously,[1-3] essentially every detailed analysis of weapons systems depends *crucially* on geometry as a key input. Therefore, the environment we seek 1) must support sophisticated tools for the generation, display, and modification of three-dimensional geometry. Further, those tools must support *solid modeling* [1,2] a rigorous form of geometric modeling which fully defines geometry *and* material in three-space. 2) There must be a means of transferring this geometry to interpretation and analysis codes through raycasting and finite-element mesh (FEM) generation. Finally, 3) the predictive analysis codes must be supported. A listing of typical high-resolution systems analyses is given in Table I. By no means exhaustive, this list nevertheless demonstrates the diversity required of current weapons engineering.

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[1] P. H. Deitz, "Solid Modeling at the US Army Ballistic Research Laboratory," *Proceedings of the Third Annual Conference and Exposition of the National Computer Graphics Association, Inc.*, held 13-16 June 1982, Vol. II, pp. 949-960.

[2] P. H. Deitz, "Solid Geometric Modeling - the Key to Improved Materiel Acquisition from Concept to Deployment", in the *Proceedings of the XXII Annual Meeting of the Army Operations Research Symposium*, 3-5 October 1983, Ft. Lee, VA, pp. 4-243 to 4-269. Also in the *Proceedings of Defense Computer-Graphics '83, International Conference and Exposition*, Washington, DC, 10-14 October 1983.

[3] P. H. Deitz, "Predictive Signature Modeling via Solid Geometry at the BRL," *Proceedings of the Sixth KRC Symposium on Ground Vehicle Signatures*, 21-22 August 1984, Houghton, MI.

Table I. List of Some Solid Model Applications (from Reference 2)

- Nuclear Survivability

- Ballistic Penetration/Behind-Armor Damage:
  - Armor Design/System Configuration
  - Survivability/Lethality Predictions
  - SPARC/Logistics Model Support

- Weights and Moments:
  - Calculation of Moment of Inertia Matrix
  - Overturning moments for Nuclear Blast Problem
  - Use of moments for Servo Fire Control calculation

- Infrared/Millimeter Wave Signatures:
  - All surfaces and materials are defined in 3 space
  - Passive radiometer prediction
  - Radar Cross Section Prediction
  - Side-Looking Radar Prediction

- Finite Element Mesh Generation (via Preprocessor):
  - Generation of 3-D Elements
  - Variable Level of Subdivision
  - Exterior Mesh for Signature Models
  - 3-D Mesh for Heat Flow Modeling
  - Static/Dynamic Stress Analyses
  - Blast/Shock Predictions

- Fire Control/Vision
  - Susceptibility of Vision Elements to Laser Radiation
  - Field-of-View of Vision Blocks

- Aerodynamic/Fluid Flow Analyses

- Mobility Models

- System Integration/Engineering Optimization

- Rational Link:
  Mission Requirements --> Quantitative System Specs

To meet the above requirements, the underlying computer environment comes into play. This environment can be understood as the hierarchy depicted in Table II.

Table II. Multiple Levels of Machine Support for CAE

[IV]	Solid Geometry, Geometry Interfaces Weapons Engineering Simulations
[III]	System Utility Codes
[II]	Operating System
[I]	Hardware

In this representation, four levels are shown. At the top (Level IV) reside the geometry and analysis codes. Level IV is supported by Level III, which includes:

- Compilers
- Text Editors
- System Subroutine Libraries
- Solid Geometric Editors
- Database Managers
- Graphical Plotting and Display Utilities
- Text Processing/Documentation Aids

and so on. These utilities, together with the specialized applications programs of Level IV, comprise what the computer user sees as the environment.

Below these, from Levels II to I, is the span from OS to hardware. The functioning of these levels is generally invisible to the user. Yet everything that he can accomplish depends in detail on the way in which these levels are structured. We will examine these domains briefly in the next section.

III. OPERATING SYSTEM

As noted above, computer hardware and the OS (Levels I and II, Table II) actually execute the utility and special-purpose user codes. It is at these lower levels that the resources of the computer are managed and all of the events coordinated. It is here that virtually all facilities and services required by levels III and IV are supported. In an attempt to explain the structure of computing, Denning and Brown[4] have recently described an OS as a thirteen-level hierarchy starting with electronic circuits at the lowest level. Finding their strict hierarchy overly idealized, we have chosen to build on their idea by generating an abstract structure model[*] shown in Figure 1.

In this illustration, the gamut of computer hierarchy is shown from the pure circuit devices at the bottom to the actual users at the top. The lowest level, SOLID STATE PHYSICS, is purely hardware and is composed of the basic magnetic domains and semiconductors of the computer. At the next level, the most basic circuit elements are collected together to form functional computing subsystems and the most elemental of storage functions. Next, these subsystems are further integrated into specific systems which handle mass storage, arithmetic, logical operations, and data communications. Through these first three levels, the computing capability exists purely as hardware implementation. However, at the next levels, system-dependent software comes into play to define how resources at the lower levels will be handled. On the left, various aspects of file system management are determined. Moving to the right, Virtual Memory (if it exists on the system) and Random Access Memory (RAM) interface to lower level (hardware) processes under the higher-level control of memory-management. On the right-hand side of the diagram are illustrated those functions associated with coordination and transfer of data (PROTOCOLS) and the lower hardware functioning as controlled by Inter-Process

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[4] P. J. Denning and R. L. Brown, "Operating Systems" in *Scientific American*, September 1984, pp. 94-106.

[*] Private communication with D. Gwyn.

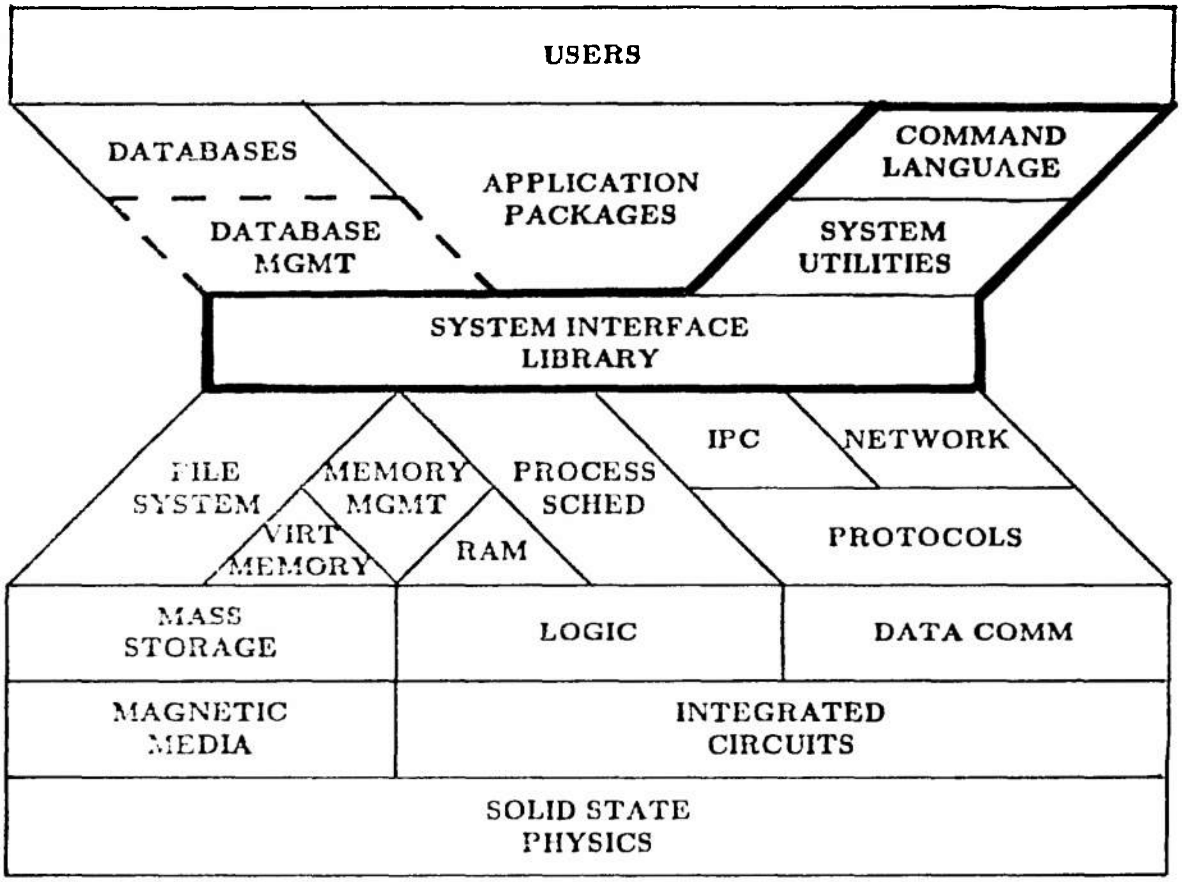

Figure 1. Abstract Structure Model of a Computer System. Pure hardware processing occurs at the lowest three levels of the diagram. At the levels spanned by the FILE SYSTEM, Operating System software resides which manages the basic hardware functioning. The emboldened block provides the resident system software through which the user communicates with the lower supporting functions. Below the SYSTEM INTERFACE LIBRARY, computation is machine specific. Above that level, a portable environment can be generated.

Communication (IPC) and Network (NETWORK) software. IPC controls inter-machine processes while the NETWORK software coordinates data flow between different machines.

These last levels are essentially software-defined and as they neck down to the bold line immediately below SYSTEM INTERFACE LIBRARY, they constitute those functions, both hardware and software, which are unique to a particular computer in terms of its hardware realization.

Immediately below the bold line, the operating system "kernel" exists. The kernel is that portion of the operating system which supports services needed by almost all programs; it exists in the main memory of the computer so as to be immediately available for execution. The SYSTEM INTERFACE LIBRARY is that level of software which fields resource requests for computations being performed under the APPLICATIONS PACKAGES (which may be user-written programs) or SYSTEM UTILITIES (which may be provided as standard user support). Applications packages may talk to System Utilities or to Database Management programs which themselves may call on the System Interface Library to access system resources.

Finally the USERS, through keyboards or other control mechanisms, interact with an Application Package or a Command Language in order to accomplish a computing task.

An important aspect of the structure depicted in Figure 1 is that each level builds on the levels below it, but hides from higher levels the specific details of operation. All levels taken together and viewed from the top define the user environment and span an enormous complexity of operation from essentially pure hardware execution at the lowest levels, to pure software implementation at the highest. The structured concept is extremely useful for coping with vast range of abstractions necessary to build a modern computer OS.

Finally, we note that the interface between Levels II and III in Table II is equivalent to the bold line underneath SYSTEM INTERFACE LIBRARY in Figure 1.

IV. MULTIPLE MACHINES AND NETWORKING

Today it is the exception rather than the rule when a single computer can suffice to provide all of the support required by many CAE analyses. This situation has been brought about by many factors. Some of them are:

- Specialized machine configurations: Clearly, by tailoring a computer for a special task, the work performed on it may be predominantly of a particular nature. For example, geometric modeling requires the support of specialized work stations especially suited for the interactive generation and display of wire-frame and color-shaded images. Because such a machine may become fully consumed by such specialized processing, aspects of subsequent analysis may best be performed on another machine, possibly in batch mode.

- Large numbers of users: Many analyses require a large number of participants. Even if those users are collocated, they may not be able to be adequately supported by a single shared machine.

- Users at separate locations: Frequently in analysis tasks, particularly in the DoD, the originators and users of data are located many miles apart. The ability to exchange and share data expeditiously becomes highly desirable.

- The evolution of machinery: Today the half-life of computer technology is something like a few years. In order to take advantage of the constantly decreasing cost of CPU cycles and memory, an organization has to be prepared to migrate its user population across a changing hardware base.

These factors, plus the extremely high cost of software, lead to the following conclusions:

- Portability and uniformity of utility and user code across machines is highly desirable. If this condition exists, then code properly developed in one such environment will easily recompile and execute in another. In addition to an enormous reduction in the cost of production and conversion of code, the user population does not have to learn multiple environments.

- Intermachine communication is crucial. This function must be supported by standard Internet Protocols and hardware interfaces.

- Independence from vendor-specific hardware is highly desirable. If all hardware must come from a single vendor in order to support a class of software, then the ability over time to shop for optimum computing value is greatly curtailed.

How then can we deal with the myriad of requirements and complexities described above? That is the subject of the next section.

V. THE ENVIRONMENT OF CHOICE

In Section II some of the general requirements for CAE analyses were described. In Section IV further considerations were introduced in order to address issues of overall efficiencies and economy. Both aspects of the problem revolve about the nature of the abstract structure model described in Section III. But in particular, only the highest levels of the structure directly impact the issues of Sections II and IV. Since the intervening levels of the OS can effectively insulate the user programs from the base-level hardware, there exists the potential to generate a *uniform* software environment which is *independent* of the detailed hardware. Through the generation of a machine-specific compiler for a portable language and a small portion of machine-dependent code, it should be possible to port system utilities and user codes from one machine to another.

This is the concept, in fact, behind the UNIX operating system.[5,6] UNIX began as a research tool within Bell Laboratories about 1970. Originally coded in machine language for a DEC PDP-7, it was recoded for a PDP-11/45 a few years later in C, a language developed at Bell Laboratories. UNIX spread rapidly through Western Electric (now AT&T) and in later versions made its way into the academic community around the mid 1970s. UNIX is characterized by an elegant structure with great flexibility and a large number of programming tools. UNIX is predominantly a set of powerful utilities which can be readily

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[5] M. Tilson, "Moving UNIX to New Machines", BYTE, October 1983, p. 266.

[6] D. F. Barlow and N. S. Zimbel, "UNIX - How Important Is It?", Datamation August 1984, p. 90.

customized for particular applications; however until recently it lacked the robustness necessary for the support of broad applications in a production environment.

The BRL began experimenting with UNIX in the late 1970s. In support of the BRL CAE requirement a solid geometric modeler was written[7] for a DEC PDP-11/34. A series of graphics utility codes were also generated to support modification and high-resolution viewing of the geometric database. Also, many formerly batch-oriented codes were ported to the UNIX environment as its utility grew through the acquisition of 32-bit processors.

Today there are two predominant UNIX variants. One now exists as a consequence of the Bell System divestiture and is supported by AT&T under the trademark UNIX System V. A large number of hardware vendors have moved to become compatible with UNIX System V. This release represents a supported product line with a large number of added utilities (e.g. expanded programming tools and aids for managing large software projects). However, there is a second substantial, and somewhat incompatible, UNIX offering developed at the University of California at Berkeley under DARPA sponsorship. This project was due largely to the perception of the academic community that previously available versions of UNIX were in need of enhancements. Berkeley 4.2 BSD UNIX supports virtual memory management, user-contributed software, a more interactive shell (job-control language) and very substantial inter-machine communication capability.

The arrival of two robust versions of UNIX has had a large impact on the computer market. One result is that UNIX (one flavor or another) has been ported to many hardware architectures.[5] Table III gives a partial list of hardware vendors to whose machinery UNIX has been ported.

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[7] M. J. Muuss, K. A. Applin, J. R. Suckling, C. A. Stanley, G. S. Moss and E. P. Weaver, "GED: An Interactive Solid Modeling System for Vulnerability Assessments," BRL Technical Report, ARBRL-TR-02480, March 1983 (UNCLASSIFIED).

Table III. A Partial List of Manufacturers Whose Computers can Run UNIX (from Reference 6).

Altos	Durango	Paradyne
Amdahl	Fortune Systems	Perkin-Elmer
Apollo	General Automation	Philips
Apple	Gould S.E.L	Pixel
Auragen Systems	Hewlett-Packard	Plessey Peripheral Systems
BBN	Honeywell	Plexus
Burroughs	IBM	Sun Microsystems
Callan Data Systems	ICL	Tandy/Radio Shack
Charles River	Intel	Tektronix
CIE Systems	Ithaca Intersystems	Televideo
Codata	LMC	Three Rivers
Columbia Data Products	Masscomp	Torch
Computer Automation	Megadata	Univac
Computer Consoles	Momentum	Western Electric (AT&T)
Computhink	Mostek	Wicat
Convergent Technologies	Motorola	Zentec
Cray	Nabu	Zilog
Cyb Systems	National Semiconductor	
Data General	NCR	
DEC	Nixdorf	
Dual Systems	Onyx	

Based on the present superiority of Berkeley UNIX in the matter of virtual memory management and ARPANET communications protocol, the BRL has chosen it for the 32-bit environment. The support of TCP/IP* has made it possible to use standard ARPANET hardware to form an internal network of BRL machines to

*TCP/IP stands for Transfer Control Protocol/Internet Protocol, and is the communication standard in use on the DARPA-sponsored ARPANET/MILNET networks.

implement inter-machine file transfer and electronic messaging. Access to the MILNET is gained through two gateway processors. Figure 2 shows a diagram of the BRLNET as it is presently configured. More than 25 machines are interconnected via IMPs (Interface Message Processors) when not collocated or via high-speed busses (> 10 Mbyte/sec bandwidth) when located adjacent to each other. In addition, members of the BRL staff have enhanced the Berkeley UNIX software through the inclusion of new mail and spooling systems, a variety of additional device drivers, bug fixes, and security enhancements (for compliance with Army Regulation 380-380, Computer Security).

However, because of the importance of the large body of useful software available in the AT&T UNIX System V release and the portability of applications developed for that environment, BRL has recently completed an emulation package which rides on the Berkeley 4.2 BSD environment but which supports UNIX System V utilities and applications developed for that environment.* Thus, it is now possible, on a single machine, to invoke either user software environment or, indeed, a combination of the two. This powerful feature of the BRL UNIX environment can be easily understood by referring to Figure 1. The cluster formed by SYSTEM INTERFACE LIBRARY, SYSTEM UTILITIES, and COMMAND LANGUAGE (emboldened outline) has two realizations. One is Berkeley 4.2 BSD; the other, UNIX System V. Simply by establishing the appropriate command directories, the desired environment can be utilized. This "plug compatibility" forms an elegant, yet simple interface. The System V package has been exported to over 50 computer sites including AT&T, Berkeley, and Gould/SEL.

The choice of UNIX has given BRL not only a powerful general computing environment for a given class of machines, but it has established a uniform set of codes across a growing number of different processors. This has contributed greatly to the conduct of many CAE functions. For example, solid geometry is often generated on one machine, analyzed on a second, and the results displayed and interpreted on a third. The underlying communications are central to this capability, while the universality of the environment minimizes regeneration of code and retraining of users.

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*Private communication with D. A. Gwyn.

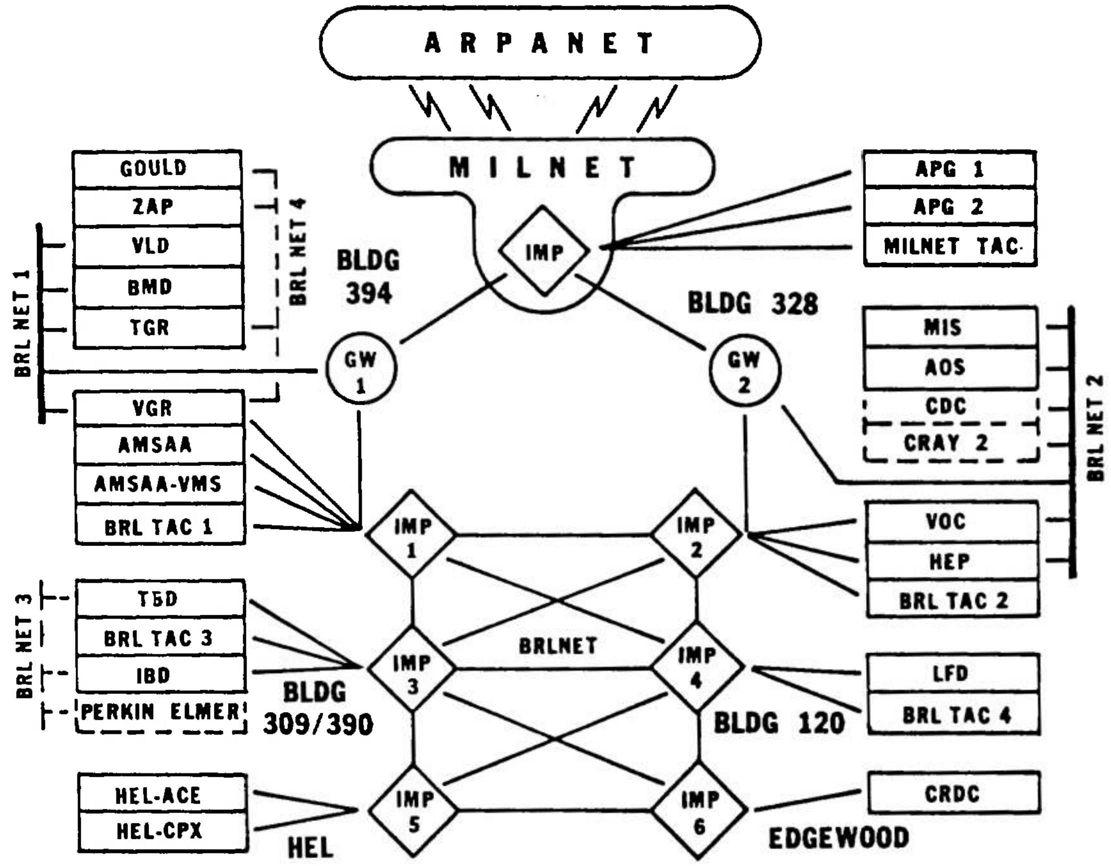

Figure 2. Diagram of the BRLNET. In the rectangular boxes are shown various mainframes and minicomputers in use at the BRL at a number of locations. An computer network ties these machines together through IMPs (Interface Message Processors). Gateways (GW1, GW2) provide passage of data between BRLNET and the MILNET/ARPANET.

Many examples of the economy brought by the use of UNIX could be cited. One will suffice. Recently the experience of a third-party software vendor was described[8] for tasks involving the porting of IBM business programs from one machine to the next. It was taking this vendor 14 months to build a library of support programs and convert his business programs from one machine architecture to the next, all for machines built by the same vendor. All of this investment was necessary simply to transfer code to a different machine. No new code was being generated. For a specific set of tasks involving the porting of 120 programs between manufacturer's machines, the job took 900 man-hours and over 5 months to complete without UNIX. With UNIX the job was accomplished in three days with about 42 hours of effort.

VI. EXAMPLES OF HIGH-RESOLUTION CAE

In this section we will briefly highlight a few of the CAE-related analyses tools that illustrate the current capability. As noted above, the reader is directed to References 1 and 2 for greater detail.

A. *Solid-Geometric Editing*

Figure 3 shows a series of screen images associated with a solid geometric editor called GED (for Graphics EDitor) written at the BRL.[7] Illustrated here is a portion of a connecting rod. On the left is the wire-frame image derived from the solid-model database. This display illustrates some of the basic geometric building blocks used to construct this particular part. In the middle of Figure 3 is the wire-frame illustration of the same part after a GED subroutine is used to "evaluate" the part. An interactive program has applied certain logic operations (such as logical subtraction) in order to remove unwanted material in the construction process. On the right is the color-shaded rendering of the part, also called interactively in the modeling process. Through these features, various stages of geometry construction can be examined.

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[8] N. Nelson, *UNIX/World*, Vol. 1, No. 6, November 1984, p. 44.

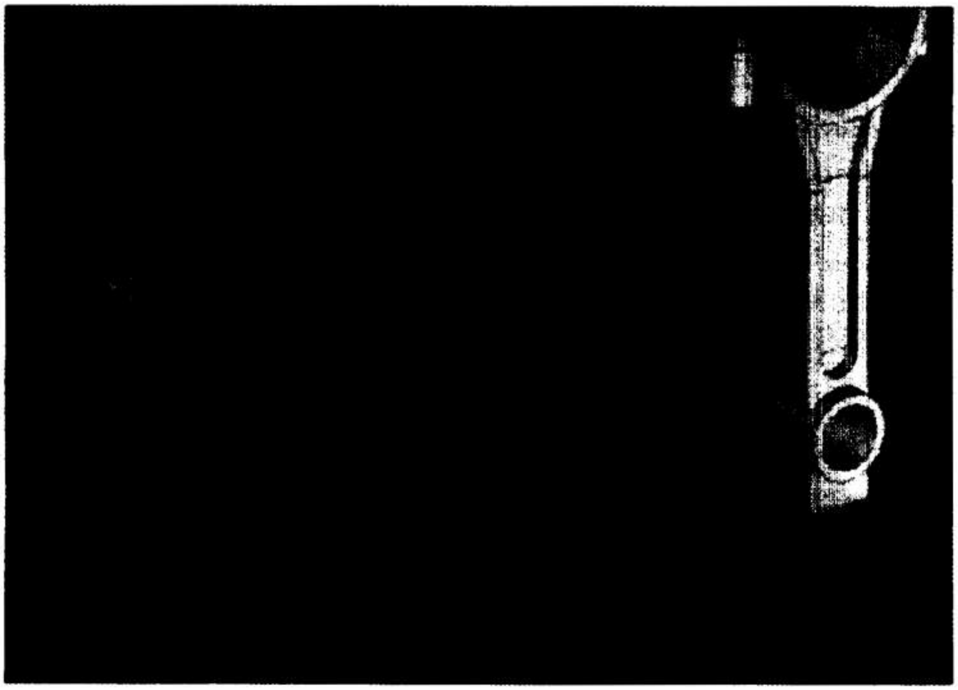

Figure 3. Screen Images in Interactive Editing. On the left is a wire-frame image of a connecting rod under construction. In the center, the same solid-model data base is shown following logic processing to illustrate the boundary file. Right-hand image shows the color-shaded rendering of the same part.

B. *Color-Shaded Imaging*

The BRL has generated many scores of models of both ground and air vehicles over some 18 years of geometric modeling. Figure 4 shows an image of the M109 Howitzer. Both internal (armor removed) and external images are shown. These pictures were computed using a ray matrix dimensioned approximately 500 x 500 intersecting the geometric database. The coordinate intersection, angle of obliquity, and component identification is calculated for each ray and used to generate the corresponding pixel in the color-shaded image. Figure 5 shows a similar image for the Bradley (M2) Fighting Vehicle.

Figure 6 shows an image of a propeller blade generated by a prototype B-spline surface modeling system called Alpha_1. The primary geometric file and the resultant color-rendering were generated at the University of Utah where Alpha_1 is under development. The image was electronically transmitted via MILNET to the BRL where it was displayed and photographed.

C. *Validation of Geometry*

Following the generation and modification of geometry, an important task is its validation. Many kinds of errors can occur including the improper scaling or location of objects. One scheme that is used at the BRL to view internal vehicle layout is illustrated in Figure 7. A set of rays one inch apart intersect a tank description. A particular slice of those rays is shown for a horizontal cut 15 inches below the tank turret ring. Different materials in the description are shown as various colors.

D. *Ballistic Penetration/Damage*

Figure 8 shows three images of a modern tank in which a hypothetical shaped-charge penetrator was fired against three azimuthal orientations of the vehicle. Various probabilities of damage from 0.0 to 1.0 (shown in the discrete color bands from white to red) show the postulated warhead effects.

Figure 4. Images of a M109 Howitzer. Both internal (armor removed) and external images are shown. These pictures were computed using a ray matrix dimensioned approximately 500 x 500 intersecting the geometric database.

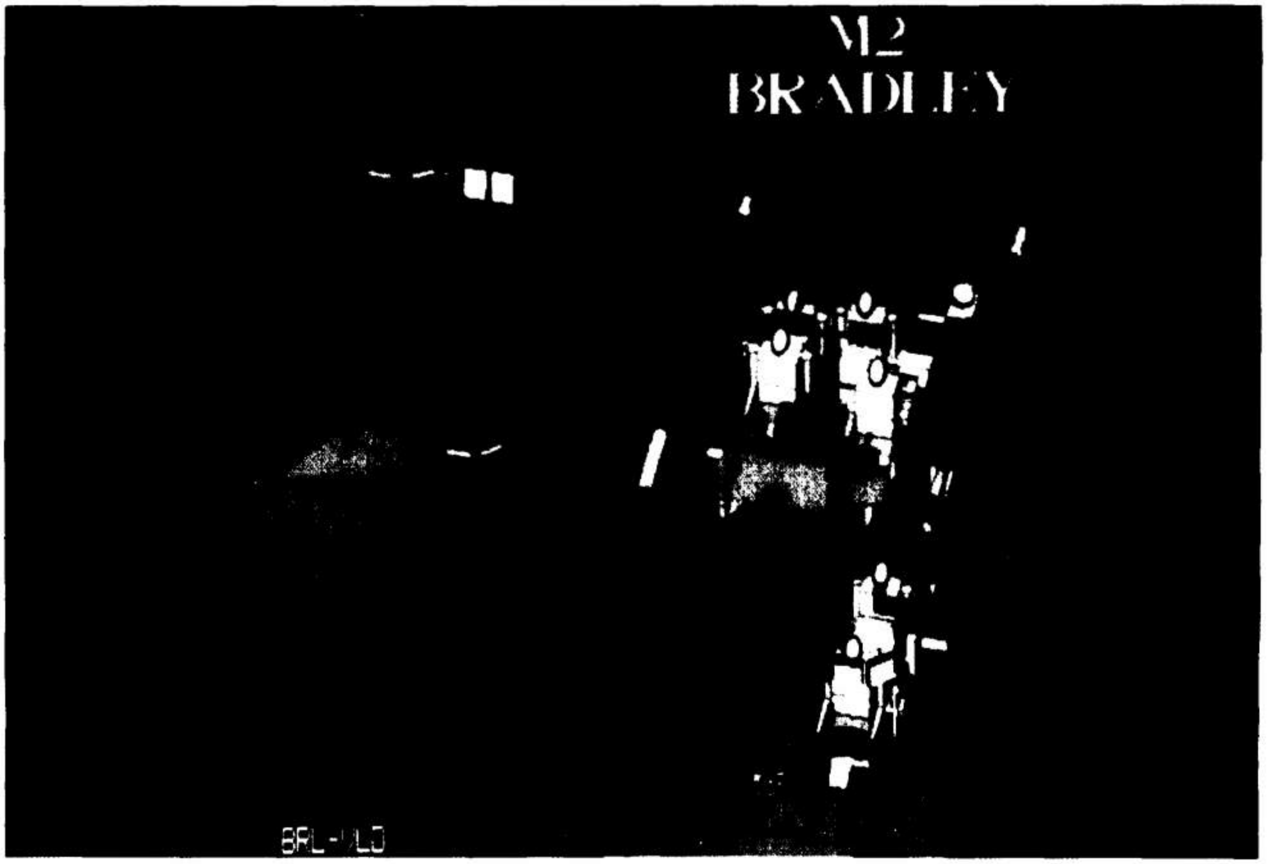

Figure 5. Bradley (M2) Fighting Vehicle. As above, internal (armor removed) and external images are shown. Such geometric/attribute files are central to the calculation of many system performance factors including survivability on the battlefield.

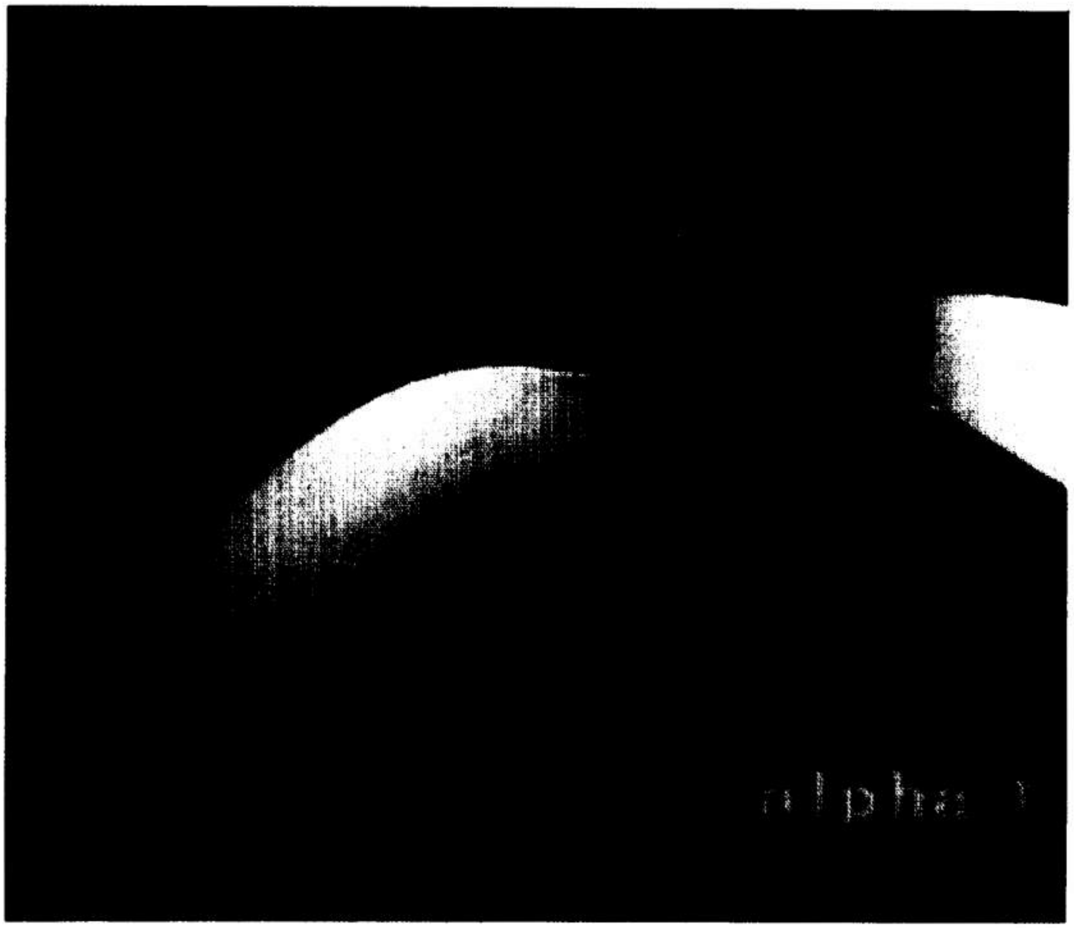

Figure 6. Image of Propeller Blade. This display was generated at the University of Utah using a B-spline based editor called Alpha_1. Accurate description of compound surfaces such as those illustrated are an important element in both predictive modeling and manufacturing.

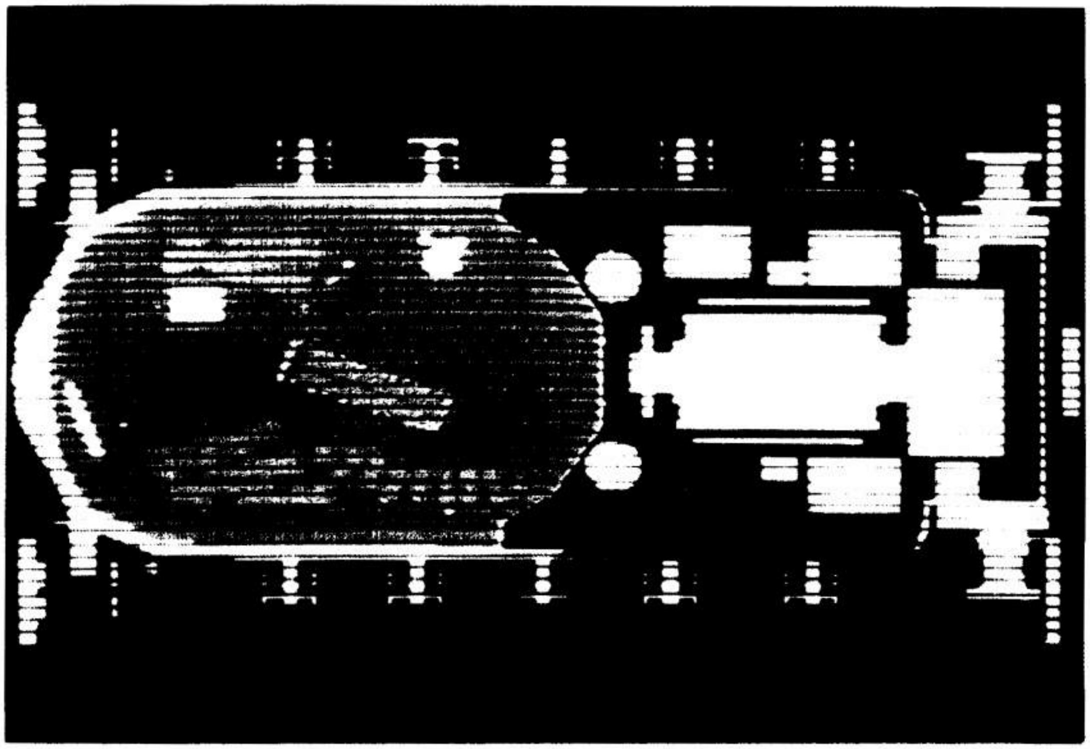

Figure 7. High-Density Ray Slice Through a Tank. A set of rays one inch apart are used to intersect a tank description. A particular slice of those rays is shown for a horizontal cut 15 inches below the tank turret ring. Different materials in the description are shown as various colors.

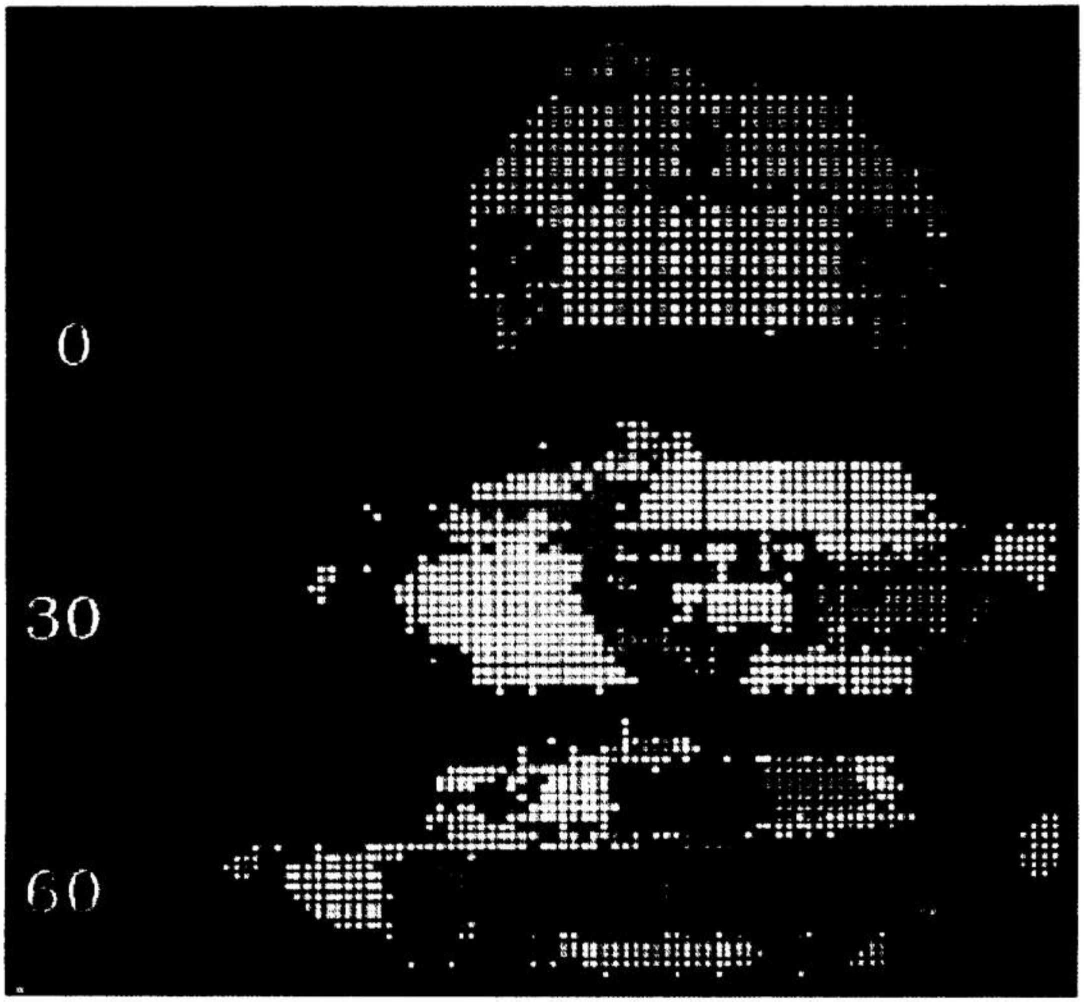

Figure 8. Assessment of Ballistic Damage. A hypothetical shaped-charge penetrator was fired against three azimuthal orientations of a modern tank. Various probabilities of damage from 0.0 to 1.0 (shown in the discrete color bands from white to red) show the postulated warhead effects.

E. *Laser Illumination of Targets*

Some modern weapons utilize a forward observer to designate an enemy target by laser illumination. A missile-borne sensor homes in on the reflected beam. In order to calculate how such a system might perform, it is necessary to calculate the laser signature that the sensor might see. Figure 9 shows four images of M48 tank using a recently developed bistatic lighting model.* In this more complicated lighting model, the light source and viewing angle can be different so that shadows are generated. Each of the four images represents a distinct angle of laser illumination; the viewing angle is fixed. Portions of the image exhibiting specular reflection are portrayed in white since they are much brighter than the general diffuse-scattered illumination shown in blue.

VII. SUMMARY

In this paper we have described the computing requirements necessary to perform high-resolution weapons-system engineering. We view this analysis as an important portion of the larger CAD/CAM milieu and an area that has not been exploited in AMC to the same extent as manufacturing technology.

Against the background of the engineering needs, further complicated by communication and portability requirements, we have shown how operating system architecture presents both an impediment and a solution to the establishment of uniform, maintainable, and sharable software tools.

Finally, we have given some current examples of high-resolution weapons analyses to illustrate the diversity and the precision that is currently possible with an integrated set of modern computing tools.

*Private communication with G. S. Moss.

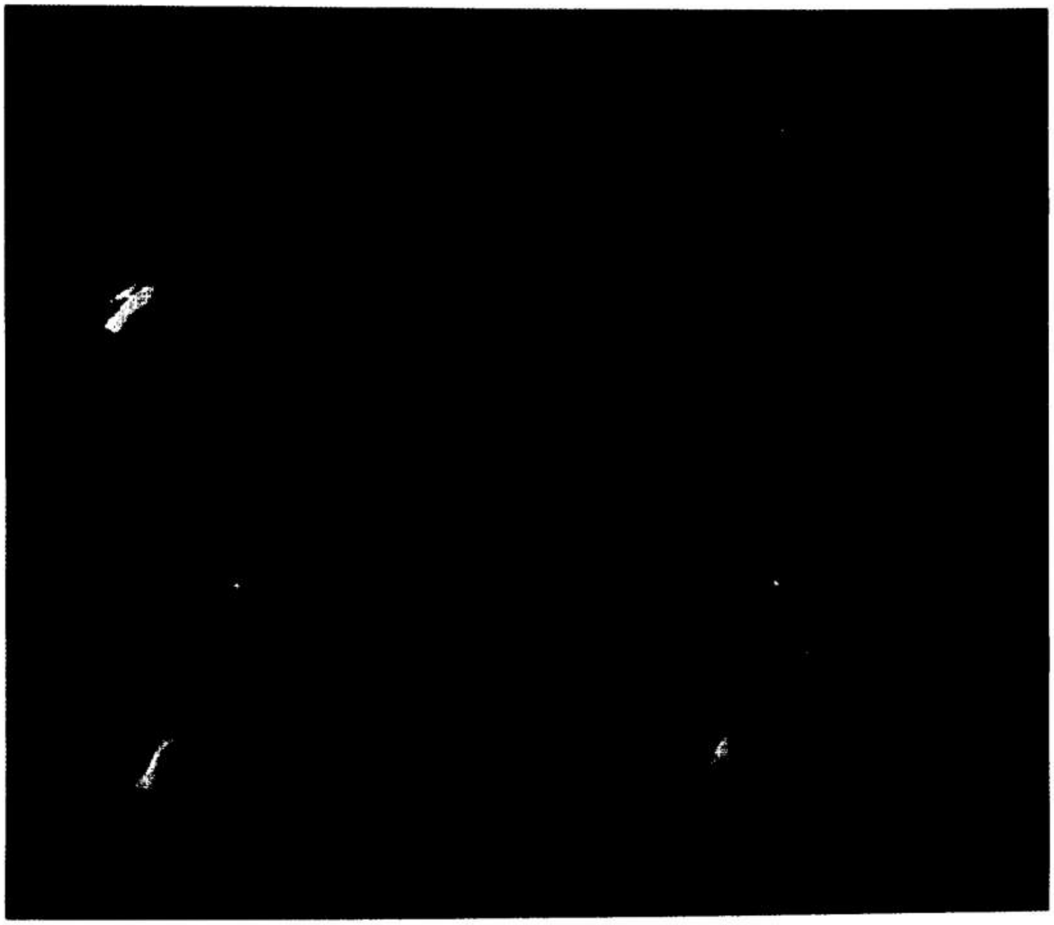

Figure 9. A Bistatic Lighting Model. The light source and viewer have different orientations. In this more complicated model, surface reflection (specular and diffuse) characteristics as well as shadows can be simulated. Each of the four images represents a distinct angle of optical illumination; the viewing angle is fixed. Portions of the image exhibiting specular reflection are portrayed in white since they are much brighter than the general diffuse-scattered illumination shown in blue.

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