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MEMORANDUM REPORT BRL-MR-3383

SOLID GEOMETRIC MODELING - THE KEY TO IMPROVED MATERIEL ACQUISITION FROM CONCEPT TO DEPLOYMENT

Paul H. Deitz

September 1984

US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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At its most abstract level, the business of materiel acquisition involves a massive task of information processing which starts with a concept and, if ultimately successful, ends with a deliverable. Most system analysts as well as program managers are aware that the key to increased productivity in such a complex process lies somehow in the application of automation. Some may view automation as the use of computer-aided drafting tools in a concept phase. Others might see it as computer-based system analyses of predictive performance

(See other side for continuation.)

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) or processor-controlled manufacturing procedures. Yet other observers may see word processing and electronic mail as centerpieces in the automated environment of the future. However, the real key to fundamental advances in the way materiel is concepted, analyzed, manufactured and delivered rests in our ability to describe and analyze geometry. By geometry we mean the complete and unambiguous mathematical definition of a system in three-dimensional space together with its complete material and functional properties, tolerances, etc. From this single unified model a series of engineering analyses can be exercised to judge the suitability of a concept to a set of requirements before a prototype is built. Later this file can be used to automate the manufacturing process.

This fact is what computer-aided design/computer-aided manufacturing (CAD/CAM) is about but with a crucial ingredient. Most CAD systems on the market today perform mainly as automated drafting stations. Because the mathematical files used for rendering generally do not describe object surfaces or material properties, they cannot be used as input to a collection of engineering analyses necessary for materiel evaluation. By contrast, an emerging technology called solid modeling is characterized by its robust, or complete, description of three-space material. Such geometry can be used as crucial input to predictive models dealing with ballistic protection, nuclear survival, infrared and structural integrity mobility, and the like.

By virtue of its long history in the analysis of materiel in both the nuclear and conventional ballistic environments, the Ballistic Research Laboratory has developed extensive experience in advanced geometric techniques. In this paper the key role solid modeling can play in weapons engineering is discussed;[1] in addition, examples of engineering analyses driven by solid modeling illustrate the capability such techniques bring to the materiel acquisition process.

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[1] For a discussion of computer-aided design techniques applied to ground and air-vehicle survivability problems, see E. P. Weaver and P. H. Deitz, "Solid Modeling in Survivability/Vulnerability," Proceedings of the Second JTCG/AS Workshop on Survivability and Computer-Aided Design, Vol. 1, 18-20 May 1982, USAF Museum, Wright-Patterson AFB, OH, sponsored by the Joint Technical Coordinating Group for Aircraft Survivability and other papers in the proceedings.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont'd)

I. INTRODUCTION

Geometry plays a central role in the evaluation of military equipment for its suitability to fulfill a particular role. Essentially every question that can be raised about system performance -- survivability, mobility, weight, maintainability -- are a function of geometry. Thirty years ago geometric data was extracted from blueprints by hand to make simple estimates of bullet penetration into aircraft structures or tank hulls. As system evaluations grew more complicated, vulnerability analysts sought ways to automate the process of passing geometry information to subsequent analysis codes.

At the Ballistic Research Laboratory that search resulted in the development of a geometric modeling technique called Combinatorial Geometry (Com-Geom)[1] which is a particular example of what is known today as Solid Modeling (SM). When an applications code is to be run, the geometric files used to represent object design are interrogated by a geometric interface and passed to the applications code itself (see Figure 1). Nongeometric data is also passed directly to the code where some system evaluation is made.

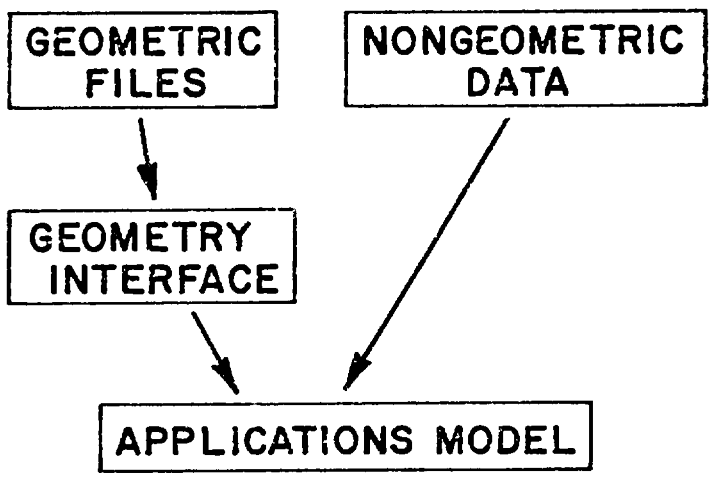

Figure 1. Geometric Data is Processed Through an Interface Where it is Combined With Other (Nongeometric) Information for Processing in an Applications Model.

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1 The original Com-Geom method was produced under contract for the BRL by Mathematical Applications Group, Inc., Elmsford, NY and was an early precursor for a current product marketed under the name Synthavision. For example,

"A Geometric Description Technique Suitable for Computer Analysis of Both Nuclear and Conventional Vulnerability of Armored Military Vehicles," MAGI-6701, AD847576, August 1969.

"The MAGIC-SAMC Target Analysis Technique," Vol VI, AMSAA TR14, April 1969. User Manual 1971.

In the past fifteen years the principal uses of solid modeling at the BRL have been to support various vulnerability/lethality codes and neutron transport models. In this paper, we want to highlight two particular issues: 1) The first relates to current progress in the generation, display, and modification of solid geometry. 2) The second is to discuss the wider application of solid geometric modeling and to give some specific examples. Table 1 shows a partial listing of uses for solid models. This list is by no means exhaustive, but gives some hint of the powerful and varied uses of geometry.

II. WHAT IS SOLID MODELING?

> Solid Modeling is an analytical framework within which three-dimensional material is completely and unambiguously defined.

This might seem to be a straight forward requirement of geometry, but the majority of commercial computer-aided design systems today do not structure their data files so as to meet the above requirement. Such systems are known as wire-frame or 2 1/2-D modelers and are quite useful for drafting and visualization. However it is not possible, for example, to pass an arbitrary ray through a wire-frame model file and know at every point along the ray the material properties.

Another way of looking at SM is the following:

> Solid Modeling is an analytical framework which serves as graphical input as well as graphical output.

This is an important property of SM data files. They are equally useful for passing geometry on to other computer codes as they are for viewing geometry.

There are generally two approaches to solid modeling.[2] They are:

(A) Constructive Solid Modeling,
(B) Boundary file Representations,
  (1) Explicit,
  (2) Implicit.

MAGIC Computer Simulation, Vol. 1, User Manual, 61JTCG/ME-71-7-1, July 1971.

MAGIC Computer Simulation, Vol. 2, Analysts Manual Parts 1 and 2, 61JTCG/ME-71-7-2-2, May 1971.

[2] For an excellent review paper covering solid modeling approaches, see A. A. G. Requicha and H. B. Voelcker, "Solid Modeling: An Historical Summary & Contemporary Assessment, " IEEE/CS Computer Graphics & Applications, March 1982.

TABLE 1. A LIST OF SOME OF THE APPLICATIONS CODES AND USES TO WHICH SOLID MODELS PLAY A KEY ROLE AS INPUT.

- Nuclear Survivability

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

- Weights and Moments:
  - Calculation of M of I 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
  - Accounts for perspective
  - 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 Intergration/Engineering Optimization

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

Com-Geom belongs to class I;[3] it is a system which uses certain geometric building blocks called primitives. Examples of primitives are various flat-surfaced volumes of four to eight sides, conic sections and ellipsoids. These entities are placed in space, possibly overlapping one another; the meaning of the overlaps is resolved by use of Boolean (or logical) definitions of the three following types:

- Union
- Intersection
- Difference*

Figure 2a) shows an example of these operations. A section of a connecting rod is modeled using a combination of planar primitives and cylinders (A through E). In its unprocessed form shown in a), the file is termed unevaluated; using only this visual prompting, the meaning of the logical operations indicated beneath a) is difficult to infer. An evaluated or boundary file is shown in Figure 2b) and illustrates the actual results of the primitive shapes when processed according to the illustrated logic operation.

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3 For a discussion of Com-Geom and a technique for interactive editing, see 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.

* The Union operation takes the combined volume of two intersecting primitives. The Intersection operation takes the common volume of two intersecting primitives. The Difference operation subtracts the intersecting volume of the second primitive from the first.

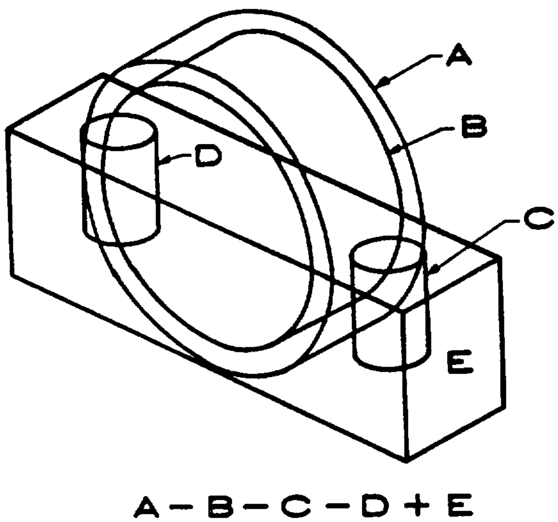

Figure 2a. Wireframe Representations of Com-Geom Building Blocks with Logic Operations

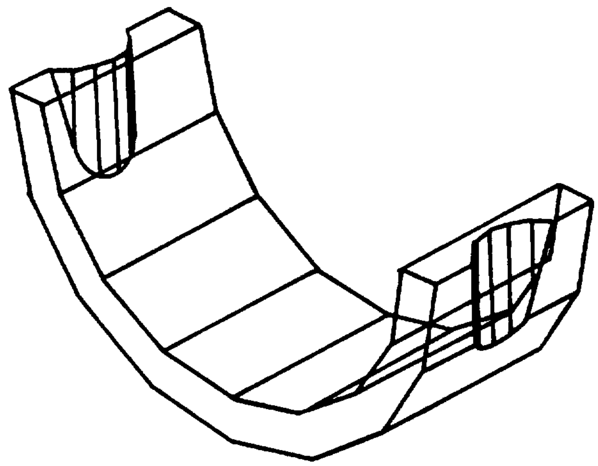

Figure 2b. Wireframe Representations of Com-Geom Building Blocks Evaluated Boundary File of Processed Geometry

Figure 2. Ability to Evaluate Geometry Removes Ambiguities in Image Interpretation.

Constructive Solid Geometry is a rather good way to start building objects (since it starts with a variety of commonly used shapes), but often the final tuning of surfaces is difficult.

Some modelers use no primitives at all, but deal entirely with surface descriptions. This approach is called the <u>Boundary File Representation (BFR)</u> and can be characterized by large numbers of flat polygonal approximations to the surfaces being modeled. Such an approach is called <u>Explicit</u> because the data base actually stores the coordinates of the surface facets. The data may actually be many sampled points over the surface on an actual object. Explicit representation has a number of serious problems among which are storage of many data points and the fixed polygonal patch size characterizing the surface at the time it is modeled. On the other hand, BFRs generally can model compound surfaces more easily than Constructive Solid Systems, and hence often have an advantage at the end of the modeling process.

A Boundary File approach which has come into use more recently is called an <u>Implicit Representation.</u> In this approach the surface of a modeled object is represented by a three-dimensional analytical function which itself is characterized by a set of parameters. Examples of analytical forms for these implicit representations are the Bezier patch and various forms of splines. When the surface is to be displayed or utilized in some applications code, points on the surface are calculated anew at the optimum spacing (or resolution) required to serve the competing constraints of surface accuracy and calculation time.

This capability is known as setting the degree of refinement. This particular method of geometric modeling holds some promise for advanced requirements where precision surface representations are required. [4,5]

Figure 3 illustrates both the use of implicit boundary representation and four degrees of refinement (or resolution).*

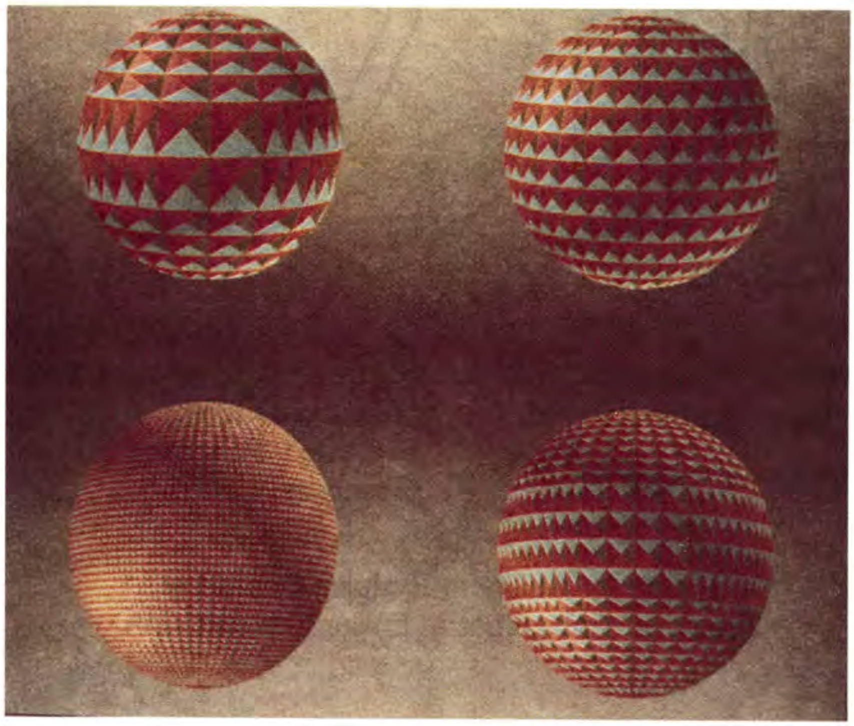

Figure 3. Illustration of Subdivision for an Implicit Boundary Representation and Various Degrees of Refinement. The same (implicit) spline representation of a sphere is used to calculate four renderings, each at different levels of refinement. None of the surface points used for rendering are stored in the data base; they are recalculated as required for a specific purpose. The cost for higher resolution in display is paid in computer cycles. (Courtesy U. of Utah, Ref. 8)

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4 E. Cohen, R. Lyche, R. Riesenfeld, "Discrete B-Splines and Subdivision Techniques in Computer-Aided Geometric Design and Computer Graphics," Computer Graphics and Image Processing, Vol. 14, No. 2, Oct. 1980.

5 E. Cohen, "Some Mathematical Tools for a Modeller's Workbench," Proceedings of Symposium on Computer-Aided Geometry Modeling held Apr 20-22, 1983 at NASA Langley, Hampton, VA.

* Private communication with R. Riesenfeld, U. of Utah.

The same spline representation of a sphere is used to calculate the four renderings, each at different levels of refinement. None of the surface points used for rendering are stored in the data base, they are recalculated as required for a specific purpose. The cost for higher resolution in display is paid for in computer cycles.

III. MANIPULATION OF COM-GEOM

At the core of any geometric model is a large set of numbers which represents the 3-space geometry being described. Unfortunately even a modest sized object requires a large numerical file for its description. In Com-Geom, for example, a simple box having an inner and outer dimension together with fuel is described by approximately 100 numbers. Any change in orientation, shape, or material entails changing a significant portion of that file.

Because of the difficulty in generating and validating files with great quantities of numbers, the task of building Com-Geom descriptions was historically quite time consuming. A full-scale tank complete with interior components could take as many as 18 months to assemble and validate. Because of this critical path in the process of vulnerability analysis, the BRL developed a graphical editor called GED.[6] This code runs on a minicomputer and gives immediate visual feedback to an operator who can initiate commands to choose viewing planes, add or delete components and modify dimensions. The organization of GED is hierarchical in nature[3] so that the designer can traverse up or down the tree structure to initiate an operation. To move higher in the tree structure is to increase the number of geometric bodies and vice versa.

GED has been used by the BRL for nearly two years, and has significantly decreased the time to generate and modify geometry. Savings factors from five to eight have been experienced.

In addition to the editing process itself, the BRL has exploited advanced techniques in image rendering made possible by current frame-buffer technology. Such processes are useful in the interpretation and validation of geometric files. Some examples of these renderings are shown in Figures 4-8. The descriptions of the M1 and Soviet BMP were each built in pre-GED days. However, the FAV (Fast Attack Vehicle), shown in Fig. 8, was built entirely with GED in about 12 hours. Various armament options (not shown) have been added to its description.

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[6] 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) (AD A126657).

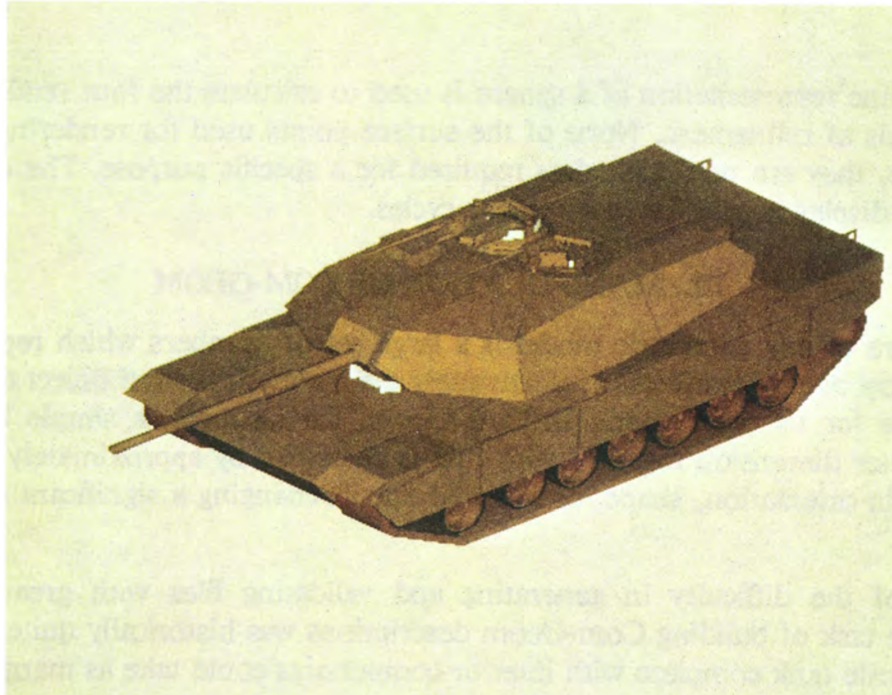

Figure 4. Color-Shaded Image of the Exterior of the M1 Tank
This model has been built using Com-Geom.

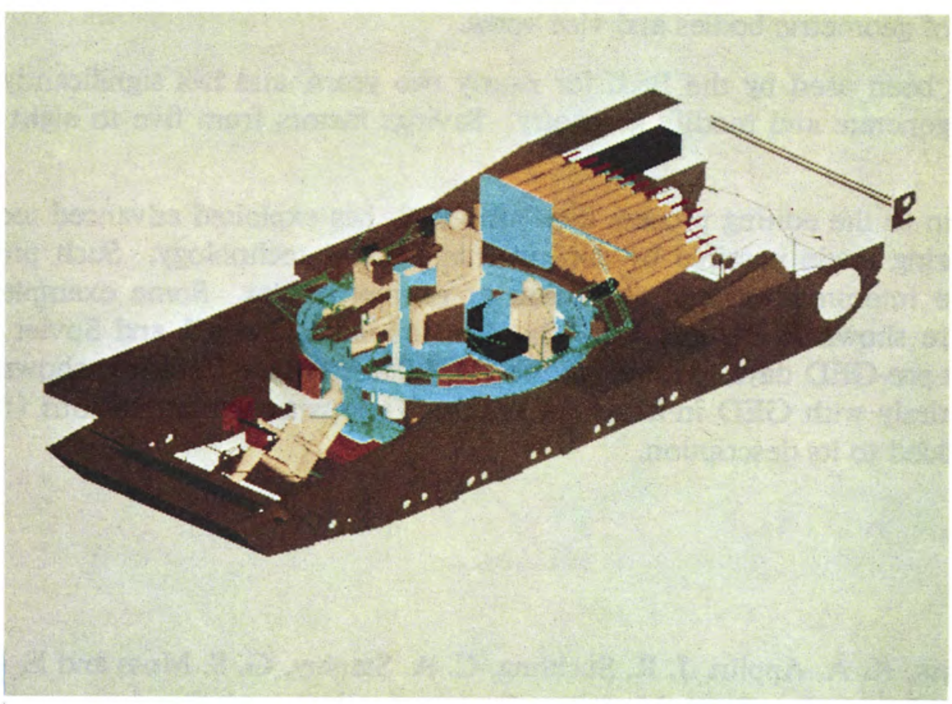

Figure 5. Similar Image of the M1 Showing the Interior
After the Exterior Structure has been Removed
Certain interior components (such as the turbine engine)
have also been removed.

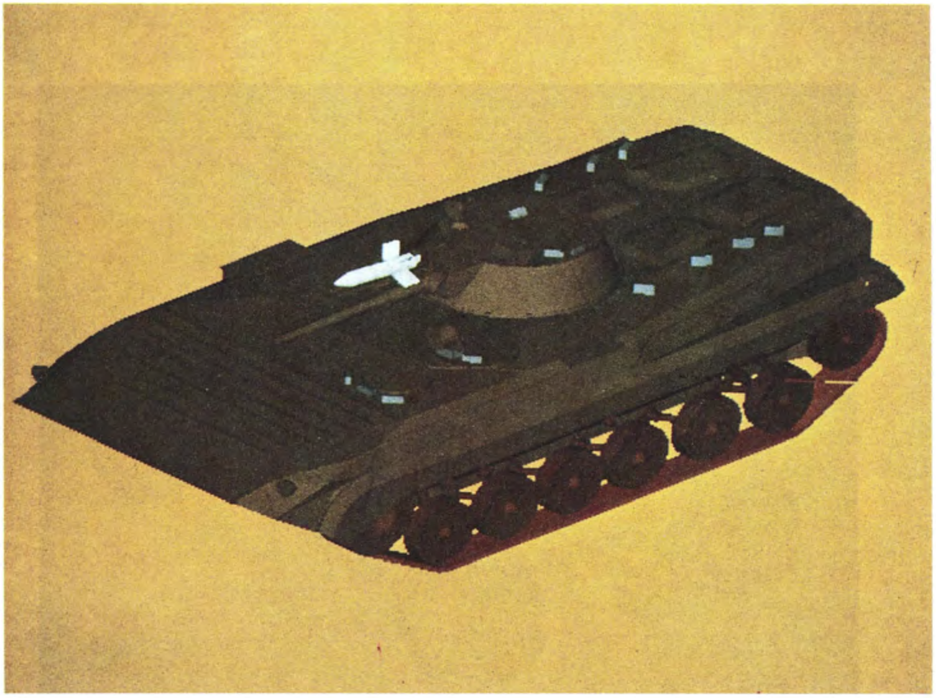

Figure 6. Image of the Exterior of a Soviet BMP Generated from a Com-Geom Description

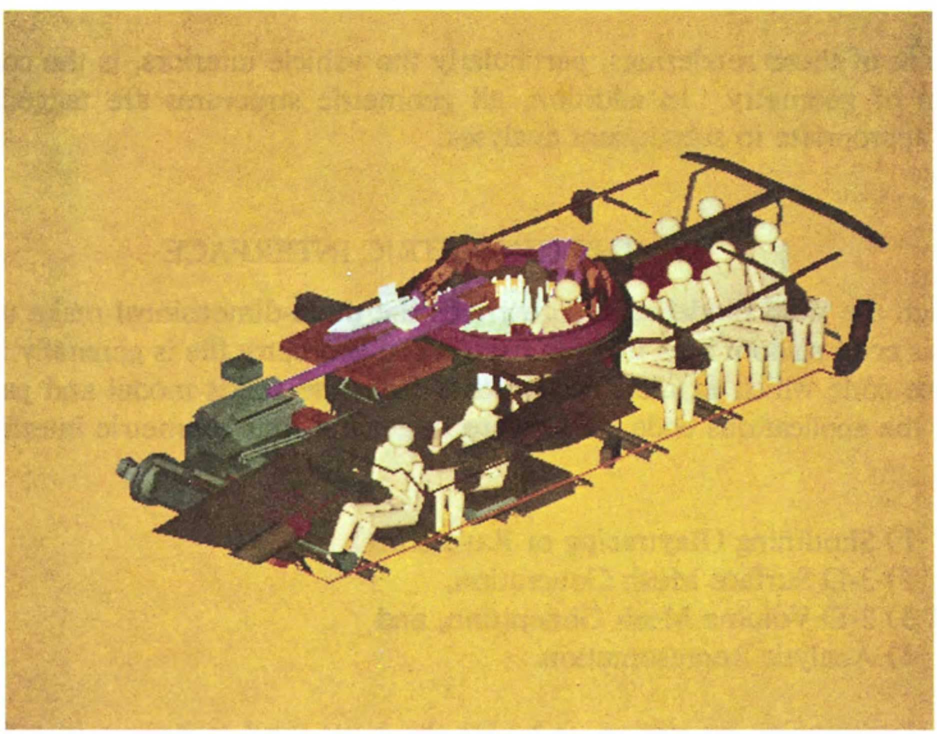

Figure 7. Interior Detail of the BMP

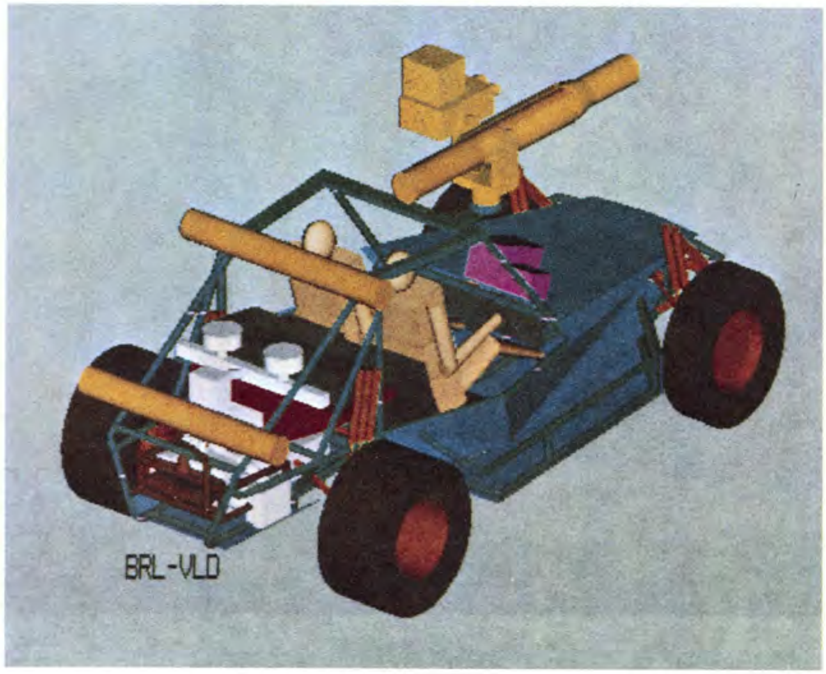

Figure 8. Color Image of the New Army Fast Attack Vehicle (FAV)

A final point of these renderings, particularly the vehicle interiors, is the complete 3-space description of geometry. In addition, all geometric structures are tagged with material attributes appropriate to subsequent analyses.

IV. THE GEOMETRIC INTERFACE

Although the solid modeling file describes the three-dimensional make up of a vehicle, the analysis code seldom sees this file itself. The geometry file is generally interrogated by an interface code which extracts certain data from the solids model and passes the information to the applications code. There are in general four geometric interface techniques. They are:

1) Shotlining (Raytracing or Raycasting),
2) 3-D Surface Mesh Generation,
3) 3-D Volume Mesh Generation, and
4) Analytic Representation.

The first, shotlining or raycasting, is by far the most used technique in vulnerability analyses. A series of rays are passed through the Com-Geom descriptions. The intersections to the primitives are calculated, the logic operations are performed, and the material assignments are made.

The code that BRL uses for this operation is called GIFT[7,8] (Geometric Information For Targets) and it is used to calculate typically thousands of ray trajectories through a target description.

Figure 9 and 10 illustrate the output of the GIFT code.*

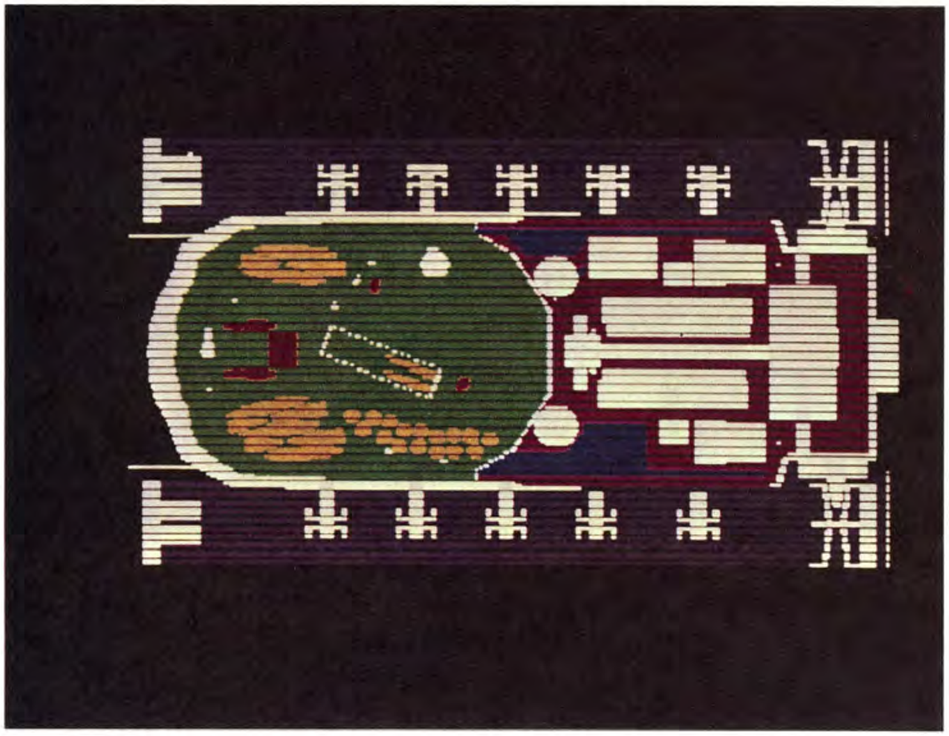

Figure 9. Color Image Showing a Set of Shotlines One Inch Apart in a Horizontal Plane Through the M48 Vehicle Below the Turret Ring. Various material structures are broken out by color.

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7 L. W. Bain, Jr., and M. J. Reisinger, "The GIFT Code User Manual; Volume I, Introduction and Input Requirements (U)," BRL Report No. 1802, July 1975. AD# A078364.

8 G. G. Kuehl, L. W. Bain, Jr., M. J. Reisinger, "The GIFT Code User Manual; Volume II, The Output Options (U)," USA ARRADCOM Report No. 02189, Sep 79, AD# A078364.

* These results are plotted by a code called RunShot written by L. M. Rybak which takes input from GIFT and plots color shotlines on a Megatek display system.

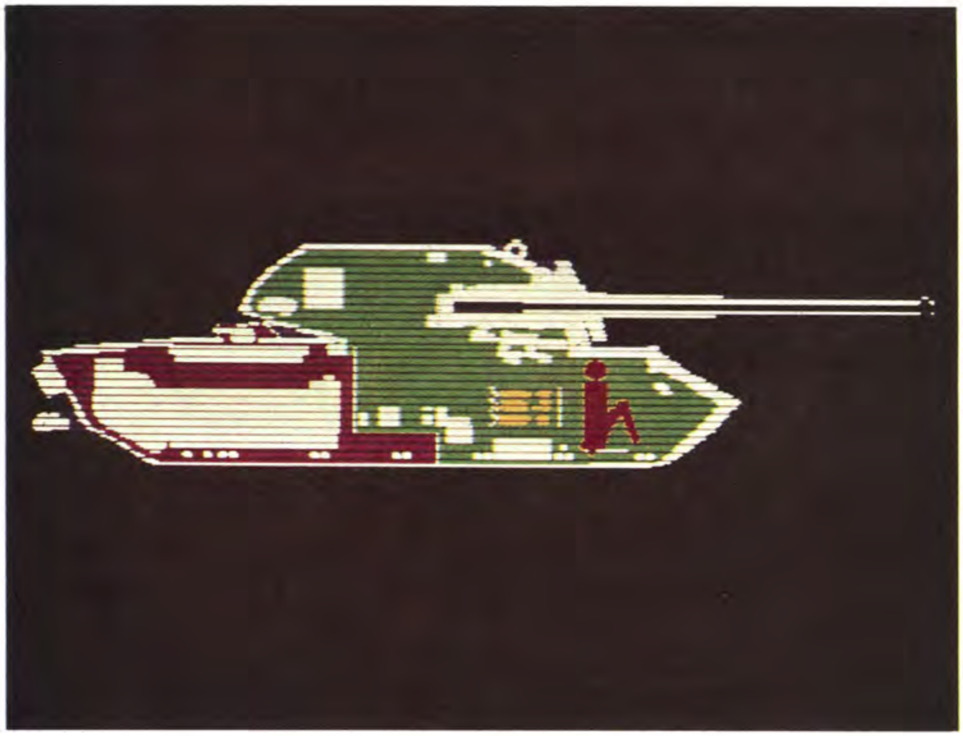

Figure 10. Same Rendering as Shown in Figure 9 for a Vertical Slice Through the M48 Center Line.

Normally in vulnerability calculations, a 4 inch x 4 inch grid is superimposed over a target from a chosen aspect angle. A single ray is fired into each grid square over the entire view. In these illustrations, the shotline density was increased to a one inch grid. In Figure 9, a horizontal set of rays has been intersected with the target description of an M48 tank. The various materials have been coded by color. White is a default color and generally includes the armor and suspension system. Green denotes crew air, yellow the ammunition, red the personnel, and burgundy the engine air. These color assignments are arbitrary and can be modified easily by the user. Figure 10 shows a similar set of rays for a vertical slice through the same vehicle.

Although shotlining provides the great bulk of geometric information to vulnerability programs, new applications require geometry information in a completely different format. Currently the BRL is developing an interface from Com-Geom to a finite element mesh (FEM) preprocessor.* This particular code is capable of generating 3-dimensional meshes on the surfaces of solid objects (i.e. a polygonal patch model) or optionally, a true 3-

* Private communication with G. S. Moss who is writing an interface between Com-Geom and a FEM preprocessor called PATRAN-G. PATRAN-G is a product of PDA Engineering, Santa Ana, CA.

dimensional solid mesh of the solid object itself. The former capability is useful for those application codes that need polygonal patch approximations to compound surface geometry. The size of the patch approximations is user definable, and can be set for the precision required in the application. Such surface information is key to the exploitation of various signature calculations of the following types:

- Radar Cross Sections
- Side-Looking Radars
- Optical Scattering
- Susceptibility of Detectors to Radiation
- Camouflage Effects
- Pattern Recognition
- Image Perspective Dependence

Three dimensional mesh generation is important for many static and dynamic structural studies as well as the following in which complete interior and exterior material information is needed:

- Heat Flow leading to Surface (and Volumetric) Temperatures
- Acoustic Signatures
- Magnetic Signatures

Finally there are certain applications in which the formal mathematical structure of a solid model may relate in closed form to an attribute of vehicle assessment. For example, the radar reflection from an armored vehicle is described by the spatial Fourier transform of the electric field over the target itself. If a solid model is based on an implicit boundary file having a mathematical form which can be directly evaluated by such a transform, then the resulting signature might be evaluated by direct analytical techniques.

V. EXAMPLES OF SOLID MODEL APPLICATIONS

In this section we will describe a few examples of applications codes which depend on solid geometric models for input. The first is an example of one of a number of point burst models in use at the BRL.

A. Ballistic Analysis

The particular model used here is called SLAVE (Simple Lethality and Vulnerability Estimator)[9] and is used to evaluate the effect of antiarmor weapons against ground

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9 F. T. Brown, D. C. Bely, and D. A. Ringers, "The Simple Lethality and Vulnerability Estimator (SLAVE): User's Manual," BRL Technical Report ARBRL-TR-02282 (AD# B055277), January 1981.

D. A. Ringers and F. T. Brown, "SLAVE (Simple Lethality and Vulnerability Estimator) Analyst's Guide," Technical Report ARBRL-TR-02333 (AD#B059679L), June 1981.

vehicles. Following perforation of a vehicle armor shell by a penetrator, SLAVE uses a simplified subroutine to evaluate behind armor spall. Basically spall is described by a cone behind the point of armor penetration. If soft components are located anywhere within the spall cone, they are counted as killed by the behind-armor debris. Hard components survive unless they are impacted by the main penetrator. This code, formerly a batch model, has been ported to various minicomputers and runs in an interactive mode with optional color plotting.[10]

Figure 11 illustrates two color-coded diagrams generated with SLAVE; these results show the performance of a particular KE penetrator against the M48 tank.

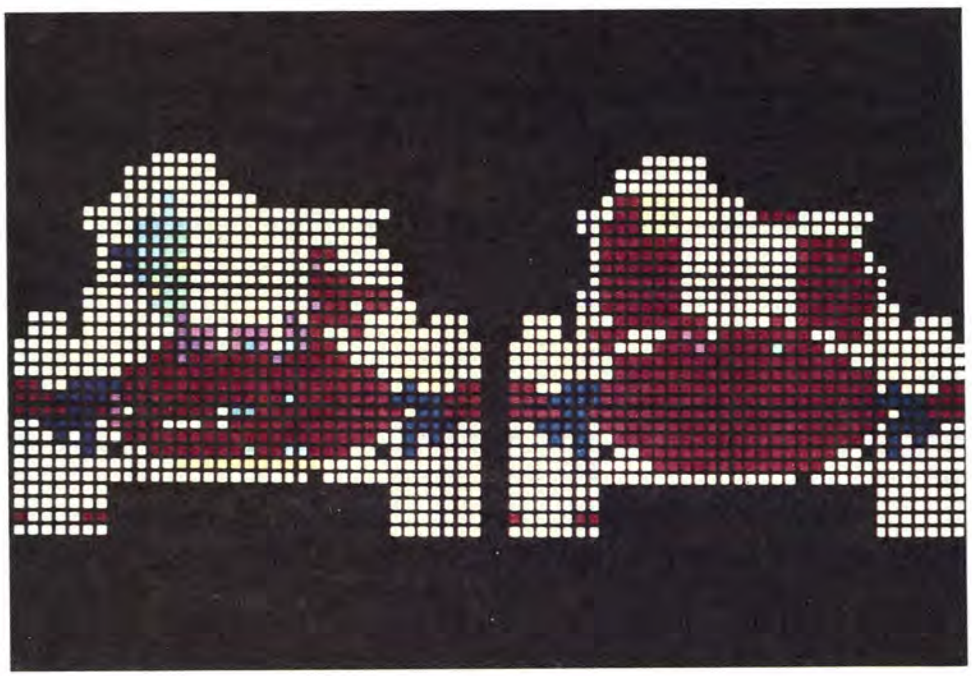

Figure 11. Illustration of Mobility and/or Firepower Kills for a Test Threat Against an M48 Tank. Color key (see Figure 12) implies numerical range from zero (white) to one (orange). Left result shows the effect of main penetrator only. Right image shows combined result for both main penetrator and spall.

The left figure illustrates the probability of an M and/or F kill (mobility and/or fire-power kill) in which only the effect of the main penetrator is assessed. The numbers are bounded by zero and one, and can be interpreted by means of the scale (below) in Figure 12. White represents zero and orange represents one.

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[10] Ref. 1 and A. Ozolins and D. A. Ringers, "ISLAVE: Interactive Simple Lethality and Vulnerability Estimator," pp. 91-99.

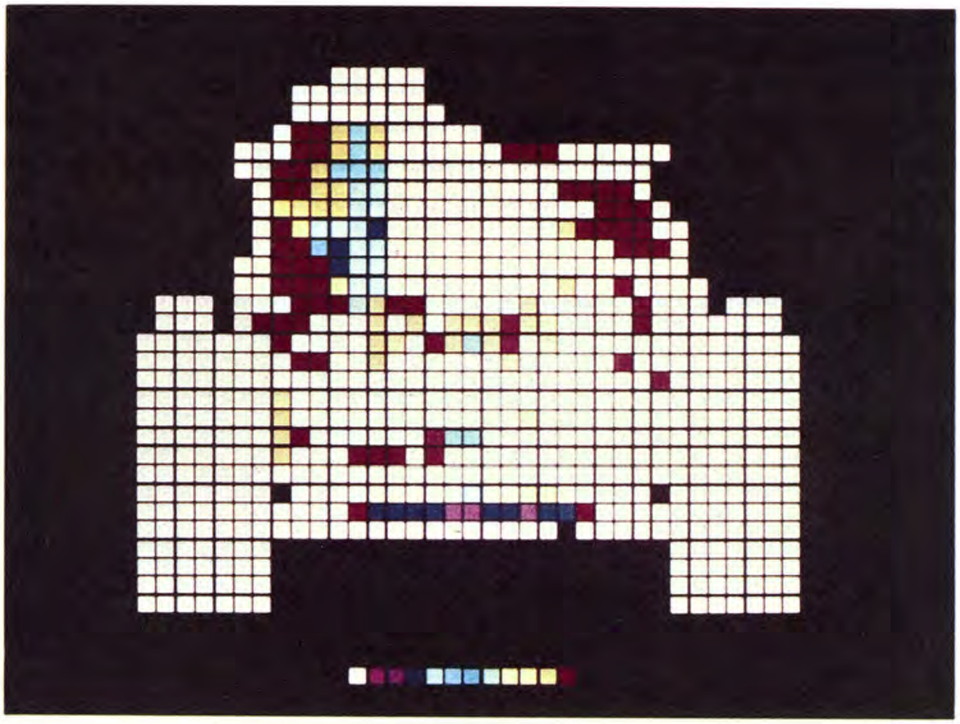

Figure 12. A Color Plot Showing the Absolute Difference Between Figures 11a and b. Numerical range of color key as described in previous caption.

On the right the calculation has been repeated evaluating the effect of behind-armor spall as well as the main penetrator. Clearly more of the target is represented in orange, indicating higher kills. Figure 12 illustrates a feature of the interactive SLAVE model--the option to subtract any two runs from each other. Here the spall and nospall calculations have been differenced showing for this penetrator/vehicle configuration the contribution of spall to the overall M/F kill. And for this particular threat/target combination, the contribution of behind armor spall to the overall system damage is clearly illustrated.

B. Nuclear Survivability

When a nuclear weapon is detonated, several threats to equipment and personnel exist. Among these threats are blast, thermal radiation, EMP and nuclear radiation. The last can be further divided into initial and residual radiation, the latter often being referred to as fallout. The BRL is primarily concerned with the initial nuclear radiation but evaluates other effects as well.

The initial radiation output from a nuclear weapon is either a prompt neutron, a neutron-induced gamma (sometimes called a secondary gamma) or a prompt gamma. In our analyses we usually only consider the total dose effects. The calculational technique used at the BRL is Vehicle Code System (VCS),[11,12] actually a combination of three codes. Referring to Figure 13, the first code calculates deterministically the transport of radiation from the source to an envelope that surrounds the vehicle. The second code makes a stochastic calculation to determine the relationship between the radiation at the source envelope and a detection point inside the vehicle. This calculation is done in what is known as the adjoint mode which amounts to a calculation backward in time for scattering from the detector point to the source envelope.

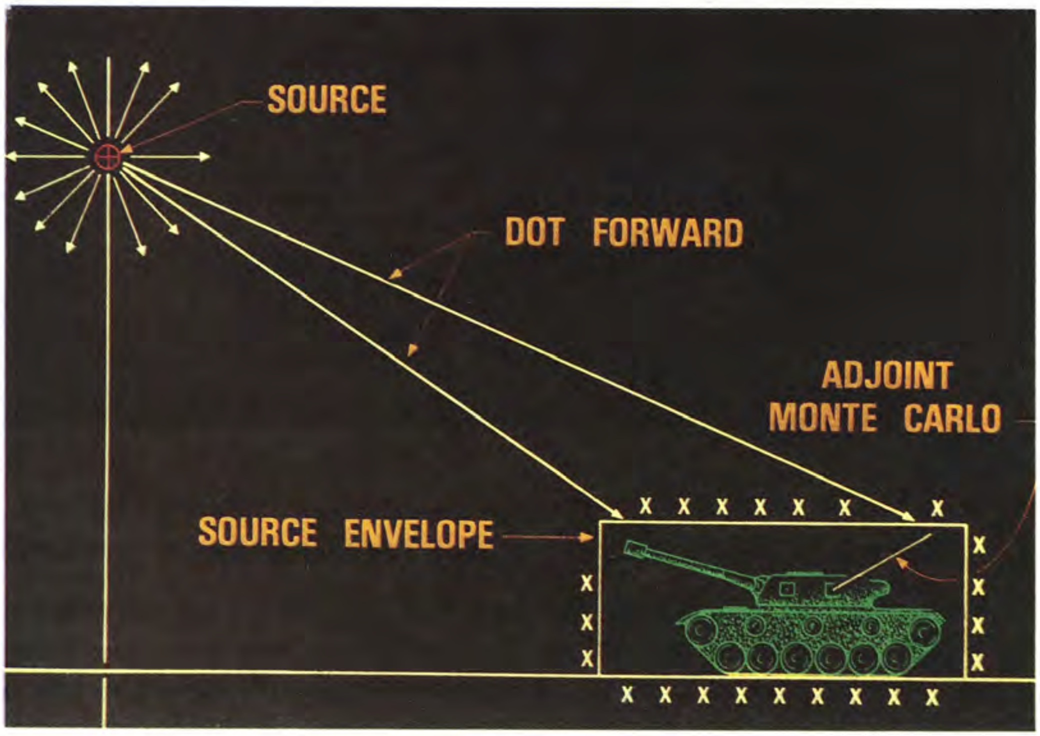

Figure 13. Ray Diagram Showing the Calculational Geometry for the Vehicle Code System (VCS). The Discrete Ordinate Code (DOT) calculates the transport of nuclear radiation from the source to an envelope surrounding a vehicle. A second calculation relates the radiation at the envelope to the total dose at some interior portion of the vehicle. The vehicle geometry itself is described using Com-Geom.

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[11]W. A. Rhodes, "Development of a Code System for Determining Radiation Protection of Armored Vehicles (the VCS Code)," ORNL-TM-4664, Oak Ridge National Laboratory, Oak Ridge, TN, October 1974.

[12]W. A. Rhodes et al., "Vehicle Code System (VCS) User's Manual," ORNL-TM-4648, Oak Ridge National Laboratory, Oak Ridge, TN, August 1974.

A Monte Carlo procedure is invoked as a given particle is traced through the Com-Geom target description. The adjoint mode is adopted for computational efficiency. A third code matches the first two codes at the source envelope boundary.

Recently such a calculation was performed for a particular US tank concept called the Tank Test Bed (TTB).* The results are illustrated in Figure 14.

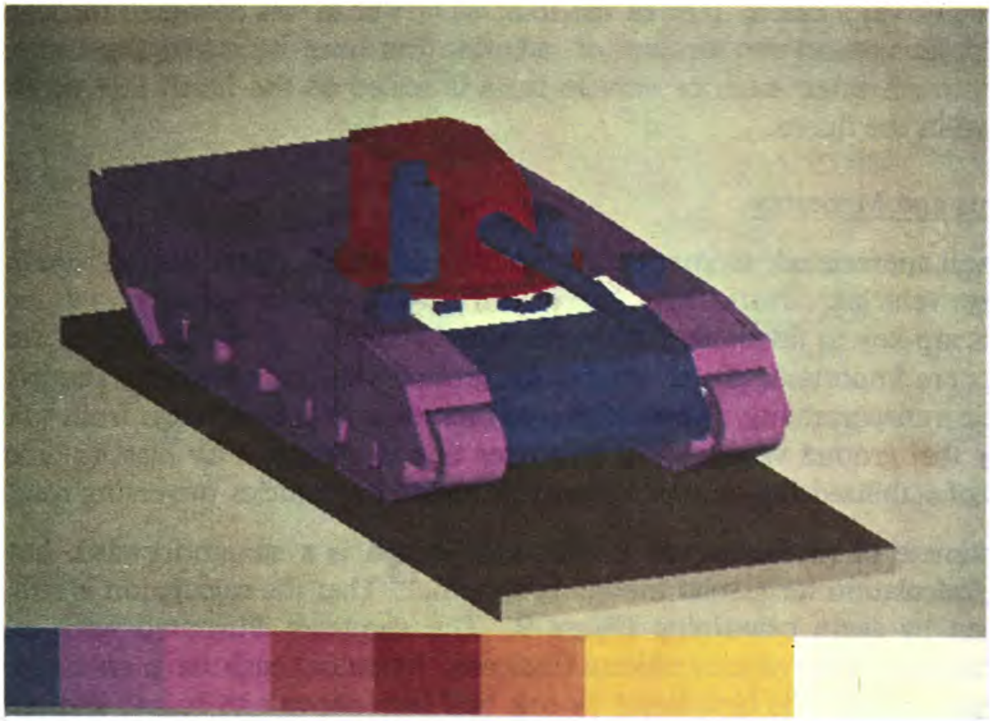

Figure 14. False-Color Image Showing Results of Neutron Transport Calculation for a Concept Vehicle Called Tank Test Bed (TTB). Total dose reaching driver was calculated by summing radiation leakage through all exterior vehicle regions. Results have been normalized to the driver's hatch (which contributed the greatest portion of radiation). Note the low-detail Com-Geom description used for this study. Color key at bottom represents range of normalized radiation dose from zero (dark blue) to unity (white).

There are two principal points. The first is that the description of the TTB illustrated here is austere --- there is a minimum of detail that can be observed in the exterior detail of the vehicle. The same holds true for the interior of the vehicle. This is because neutron

* J. W. Kinch and A. E. Rainis, "Nuclear Vulnerability Analysis of the Tank Test Bed (TTB) in an Initial Nuclear Radiation Environment," BRL Technical Report ARBRL-TR-02552, March 1984 (AD B080980).

transport problems are sensitive only to rather gross distribution of material and thus geometric detail is insignificant in such analyses. Second, the vehicle is displayed using a false coloring scheme. In this study the total radiation dose reaching the driver's head was calculated while monitoring the specific exterior portions of the vehicle through which the radiation leaked. In Figure 14, an attempt has been made to render the portions of the vehicle contributing most greatly in brighter colors, those contributing less in the duller part of the spectrum. The results have also been normalized to the radiation entering through the driver's hatch; 60% of the total driver's dose was delivered through the hatch, and for the illustration that amount of radiation has been normalized to unity. Radiation entering through other exterior vehicle parts is scaled to the hatch flux according to the code shown in the figure.

C. Weights and Moments

As is well appreciated, moments and products of inertia play a central role in the design of military vehicles. Particularly for aircraft, the center-of-gravity and inertia-related parameters are key to favorable performance and stability. Even for ground vehicles these parameters are important. Total weights for ground vehicles are always needed for assessment of air transportability. Applications of moments of inertia range from calculating the probability that ground vehicles will turn over due to a nuclear air blast to predicting aiming errors of stabilized fire-control systems mounted on vehicles traversing rough terrain.

The estimate of moments and products of inertia is a straightforward, but somewhat laborious, calculation for a solid modeling system.[13] That the calculation is straightforward can be seen by again examining Figure 9. The shotlines illustrated were calculated on one-inch centers. The various objects (indicated by color) each have an assigned density. In effect, each shotline is broadened by one half inch above and below, and left and right. This gives a (one-inch) square cross section of uniform mass between material interfaces as the shotline progresses through the vehicle description. The laborious aspect of the calculation involves setting the effective density of various components properly and seeing that the predominant vehicle constituents are in place.

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[13] See for example G. A. Blass, "Theoretical Physics," Appleton-Century-Crofts, NY (1962), pp. 102 ff. By these techniques calculations of the principal second moments and cross products of inertia can also be made. Often these mechanical design parameters have been unavailable to the traditional engineer due to the computational overhead.

Moment-of-inertia and center of mass calculations were performed recently* using the Com-Geom description of the M60A3. The changes of the A3 version over the A1 include a new suspension system, a new turret and fire control system, and new tracks. A one-inch shotline grid was used and the calculation was performed along each of the principal axes (See Figure 15). The total number of shotlines computed came to about 76,500, and the results of the three runs were averaged.

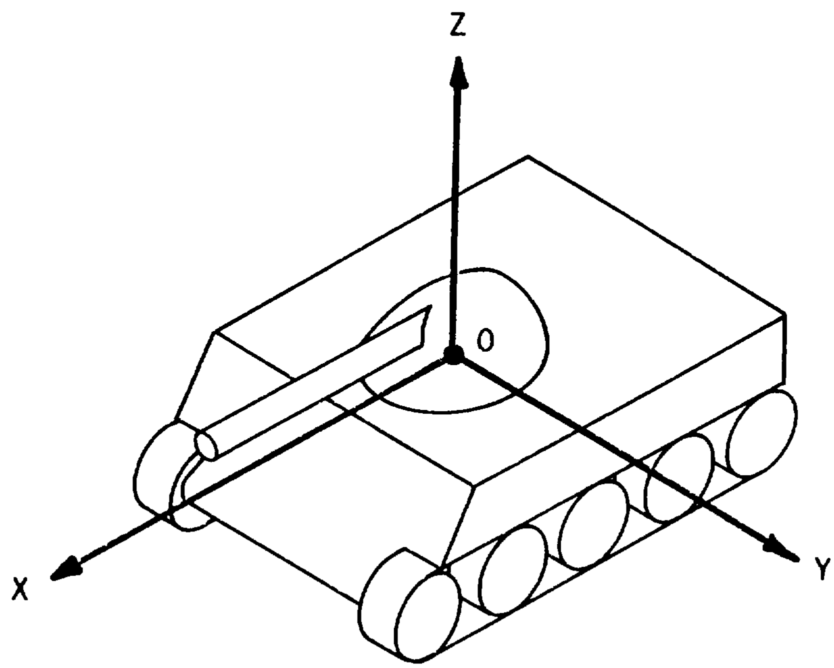

Figure 15. Schematic Showing Orientation of Axes for Moment and Center-of-Mass Calculations for M60A3.
(Origin of coordinates resides at the center of the turret ring.)

Table 2 shows the calculation of center of gravity comparing the Project Manager's data and the BRL calculations. The origin of the coordinate system resides at the center and base of the turret ring. Given the length of this vehicle (approximately 20 feet), the PM's and calculated results are within a few percent agreement. The results for moments of inertia are given in Table 3. Again the agreement is quite good.

---

* Private communication with J. H. Walter.

TABLE 2. A COMPARISON OF THE CENTER OF GRAVITY FOR THE M60A3 MAIN BATTLE TANK.

The upper figures are due to the Project Manager, M60, and the lower numbers are the result of a GIFT calculation. Coordinate axes are shown in Figure 15. Origin resides at the center of the turret ring.

	X	Y	Z	
PM M60 FIGURES:	-15.4	-0.6	-14.4	INCHES
GIFT CALCULATION:	-20.3	-0.4	-15.6	INCHES

TABLE 3. MOMENT OF INERTIA (in lbm-ft^2) ABOUT THE CENTER OF GRAVITY FOR THE M60A3 TANK. Left are the PM M60 data; right are the results of the GIFT Calculation.

	PM M60 DATA	GIFT CALCULATION
I_{xx}	1.67×16^6	1.55×10^6
I_{yy}	4.95×10^6	5.12×10^6
I_{zz}	5.46×10^6	5.59×10^6

One further application of these calculations worthy of mention is their use in fire-control predictions. Clearly the slew rate for a tank turret depends on the distribution of mass. Using our graphics editor, it is a straightforward process to add or delete ammunition in a turret bustle or to reconfigure the armor and rerun GIFT for each configuration to generate various sets of moments. Each set can be fed in turn into a servo-control model to see how the fire control mechanism is affected by configuration.

D. Susceptibility of Vision Elements

The BRL was recently asked to evaluate susceptibility of various vision ports on armored vehicles to optical irradiation. One vehicle for which this study was made is the Soviet BMP, illustrated again in Figure 16. This rendering is different from that shown in Figure 6 for here the commander and driver vision blocks are illustrated in blue. The

GIFT code was modified* to calculate the area of a particular vision block exposed to optical radiation from a given aspect angle.

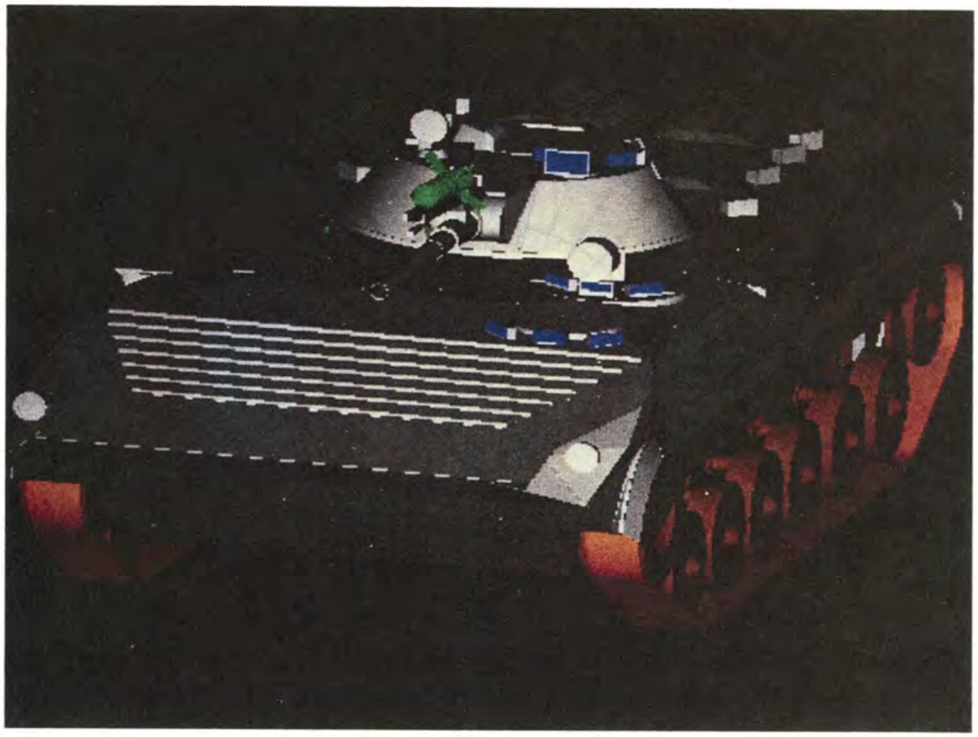

Figure 16. Color Shaded Image of Soviet BMP.
The blue colors highlight the commander and driver vision blocks.

For this study the elevation angle was held at zero and the azimuthal angle was varied over the frontal arc. Figure 17 shows the results for the commander's forward periscope. The cardioid plot gives the percent area of his vision block that would be illuminated by a laser versus azimuth angle. The large reduction in illumination on the commander's right is due to the obstruction caused by the mounted sagger missile.

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* Private communication with G. G. Kuehl.

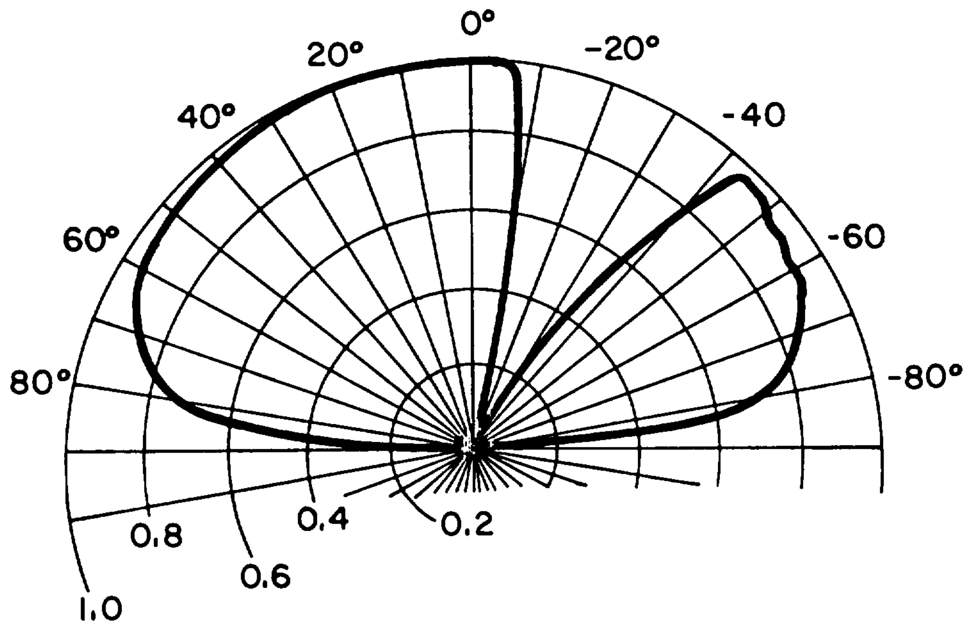

Figure 17. A Polar Plot Illustrating the Fraction of the Commander's Forward Site Illuminated by an Optical Source as a Function of Azimuth Angle (Zero Degrees Elevation).

An important related problem with which vehicle builders must deal is the design and placement of the vision elements so as to optimize the exterior field-of-view for the vehicle occupants. When the viewing system for a current fighting vehicle was initially built (presumably without the assistance of a computer-aided vision program), the result was a substantial blind spot in one portion of the commander's field-of-view. At some expense the system was redesigned to eliminate this problem.

With the appropriate application code, a solid model can be used with inside-out ray-casting to give the view from inside a vehicle through any vision port or window. Such an option is available in a solid modeling package called Euclid* and could be indispensable in the design of vision systems.

E. Infrared Modeling

Solid Modeling can also be applied to the problem of infrared signature analysis. In the design of smart munitions it is important to know the nature of vehicle signatures over a range of detection bands and signal processing schemes. In order to estimate the infrared

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* Euclid is a product of MATRA Corporation of France and is distributed by MATRA DATAVISION, Inc., Boston, MA.

performance of one smart system called SADARM,[14] a series of measurements in the 8-12 micron band were made for a Soviet T62 tank under various operating conditions. For each set of conditions, a complete thermal signature was gathered over the vehicle surface. The measured temperatures were then associated with the corresponding exterior regions of the Com-Geom description. Such an approach, although not predictive, assures that the effect of sensor aspect angle is accurately accounted for in the subsequent simulation.

Figure 18 shows a (Com-Geom generated) color-shaded image of a T62 Soviet tank. And Figure 19 shows a thermogram of the tank from the same aspect angle (90,45). The false color image illustrates the signal strength in the 8-12 micron band; this data was taken during clear night time operating conditions, and the color scale represents a range of about 18 to 35 Degrees C. Although this is not an example of predictive modeling, the solid model serves an invaluable role in achieving true image perspective in the sensor simulation.

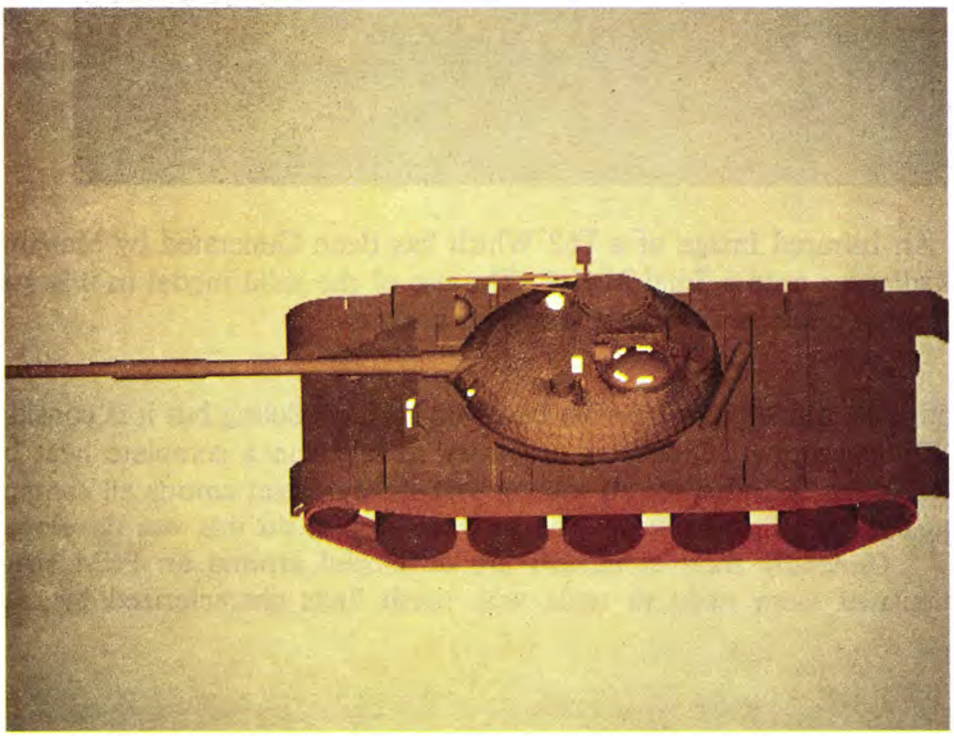

Figure 18. A Color Shaded Image of a T62 Tank When Viewed From a (90,45) Degree Aspect Angle.

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[14]J. R. Rapp, "A Computer Model for Estimating Infrared Sensor Response to Target and Background Thermal Emission Signatures," BRL Memorandum Report ARBRL-MR-03292, August 1983 (AD B076976L).

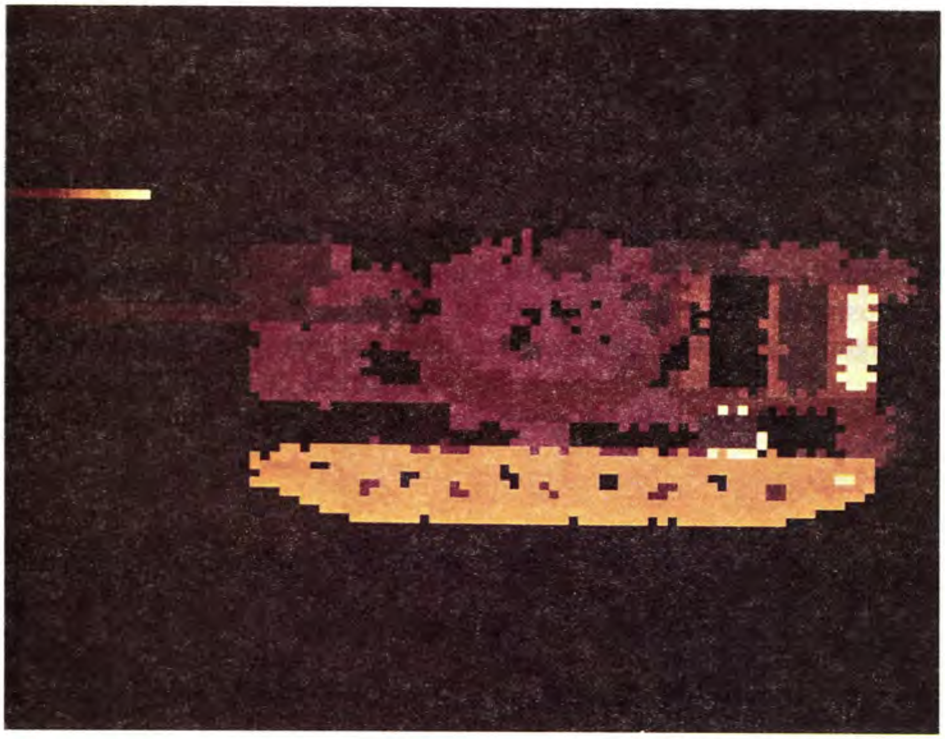

Figure 19. An Infrared Image of a T62 Which has Been Generated by Mapping Measured Radiances onto a Solid Model. The use of the solid model in this way assures the proper effect of aspect angle in later analyses.

Actual predictive IR modeling is possible based on solid modeling but it is considerably more difficult. To make predictions it is necessary to calculate a complete heat budget throughout the vehicle accounting for all sources and sinks of heat among all components including the rates of heat flow as well. The methodology to do this was developed but never validated.[15] Generally thermal models are developed around an FEM structure. Heat flow is calculated from node to node with mesh links characterized by coupling coefficients.

VI. SUMMARY

In this paper we have described some of the principal techniques used in solid modeling as well as illustrated ways in which this discipline can be applied. We have asserted that essentially all engineering models which attempt to predict system performance must be

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[15] J. R. Rapp, "A Computer Model for Predicting Infrared Emission Signatures of An M60A1 Tank," BRL Report No. 1916, AD#B013411L, August 1976.

supported by solid geometric descriptions. Although solid modeling was developed principally for ballistic and nuclear studies, its application is far wider than commonly realized.

The applications described above belong wholely to the R & D cycle of weapons systems. The title of this paper implied a much larger role for solid modeling, and indeed it has one. Materiel development generally starts with a vague concept. In a series of iterative analyses, the concept is progressively refined. At some point the concept is either passed on for prototyping or abandoned. We believe that Solid Modeling should play a key role in providing the critical geometric/materiel data base to support a broad group of engineering analyses. Subsequent to this phase, the data base should be passed over to the manufacturing cycle where substantial savings in time and improvements in accuracy could be made. For in fact much of the computer-aided manufacturing data would already have been generated.

Figure 20 attempts to illustrate the process of materiel acquisition from concept (in the R & D phase) through manufacturing. At the heart of the process is the Solid Geometric Model (SGM) data base. In the upper half, layered around the data base are the applications codes for suitability assessments; the supporting electronic environment makes it possible to move and share data quickly. In the lower half the refined concepts become reality through computer-aided manufacturing techniques. Somewhat ironically, the Army has paid considerably more attention to the automaton of this latter stage of materiel development than to the concept and engineering phases. Based on the enormous monetary commitments made to the manufacturing cycle, this attention is not surprising. However, the potential to achieve maximum weapon-design optimization can only occur in the engineering phases of development, not by altering constructed materiel by means of product improvements (PIPs) after manufacturing. Only by means of computer-aided geometric techniques carefully and broadly applied to weapons engineering can we expect to achieve the optimum performance, reliability and timely delivery of future military systems.

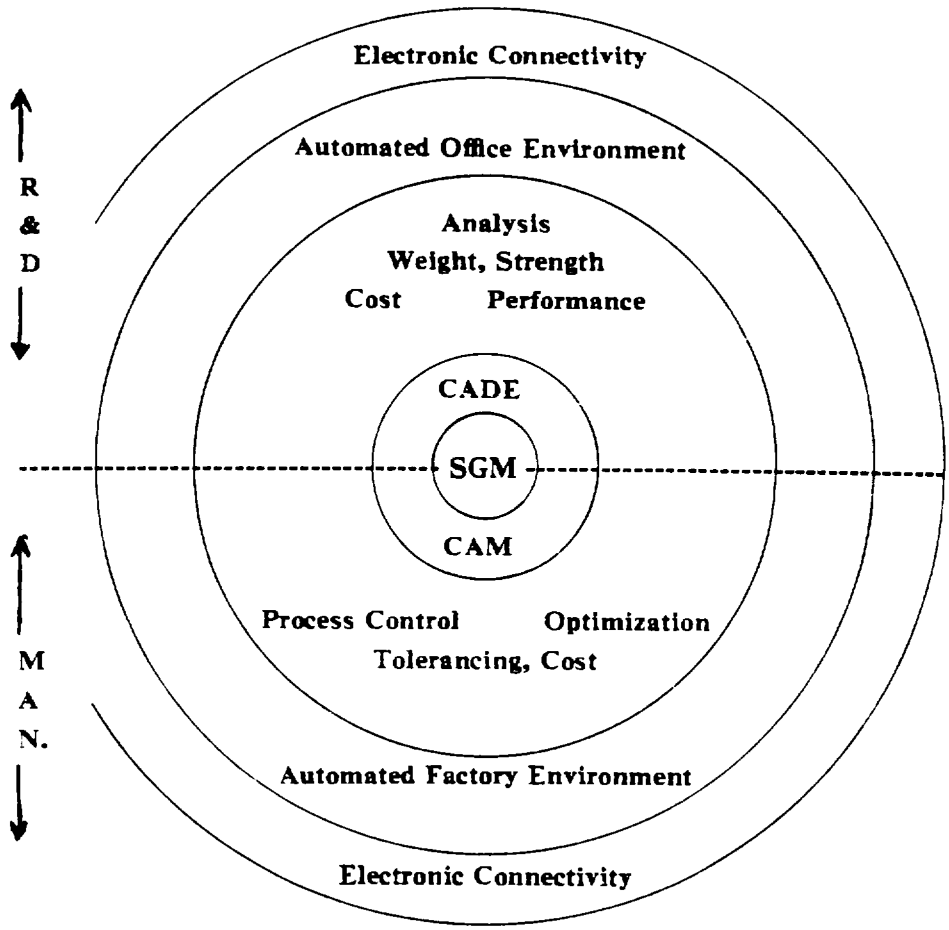

Figure 20. A Diagram of the R&D (upper half) and Manufacturing (lower half) Phases of Materiel Development. At the heart of both major cycles is the Solid Geometric Model (SGM) data base which unites geometry with material (attribute) properties. Around the shared data base are the supporting codes and processes all linked via electronic media.

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