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ISSUES IN AUTOMATIC OBJECT RECOGNITION: LINKING GEOMETRY AND MATERIAL DATA TO PREDICTIVE SIGNATURE CODES

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The principal focus of Automatic Object Recognition (AOR) involves the generation of appropriate algorithms to process the output of multi-spectral sensor arrays. Given the high dimensionality that characterizes the signatures of targets of interest, it is normally impossible to satisfy the need for raw signature data by means of measurement records alone. Individual sensor characteristics in conjunction with aspect-angle dependence, target and background configuration (singly and in synergism), and multi-spectral tradeoffs inexorably lead to a requirement for predictive signature modeling methods. By means of this stratagem, a measured signature database can be leveraged significantly, improving the fidelity of the simulation. Irrespective of the specific representation used for three-dimensional geometry and material database, rarely does a predictive signature application code read that database directly. Rather, a specific interrogation method is used to pass particular geometric and material attributes to the application code. Clearly the nature of the physics employed in the application is both enabled and constrained by the form of the interrogation process used.

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Issues in automatic object recognition:
Linking geometry and material data to
predictive signature codes[‡]

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ABSTRACT

The principal focus of Automatic Object Recognition (AOR) involves the generation of appropriate algorithms to process the output of multi-spectral sensor arrays. Given the high dimensionality that characterizes the signatures of targets of interest, it is normally impossible to satisfy the need for raw signature data by means of measurement records alone. Individual sensor characteristics in conjunction with aspect-angle dependence, target and background configuration (singly and in synergism) and multi-spectral tradeoffs inexorably lead to a requirement for predictive signature modeling methods. By means of this stratagem, a measured signature data base can be leveraged significantly, improving the fidelity of the overall simulation.

Irrespective of the specific representation used for a three-dimensional geometry and material database, rarely does a predictive signature application code read that database directly. Rather, a specific interrogation method is used to pass particular geometric and material attributes to the application code. Clearly the nature of the physics employed in the application is both enabled and constrained by the form of the interrogation process used.

In this paper, several examples of predictive radar codes are given, illustrating several strikingly different ways of linking geometry to applications. Following those examples the interface methods known to the authors will be described. While many of the techniques have already been implemented, some are currently in development. In addition, the utility of various techniques will be related to particular application codes.

1. INTRODUCTION

The principal focus of Automatic Object Recognition (AOR) involves the generation of appropriate algorithms to process the output of what are often multi-spectral sensor arrays. The generation and testing of such algorithms necessarily require the full panoply of desired object (target) signatures as well as undesired and unavoidable (clutter) signatures. Even ignoring the sensor response characteristics (time and space resolution, polarization, noise, etc.), both the target and clutter signature sets are unbounded even for a single frequency, let alone in multi-spectral domains. The unboundedness is strictly true for these signature sets and most probably so even for derived statistical measures.

Given, therefore, the requirements of a typical AOR project for copious signature files for algorithm generation and testing, it is normally impossible to satisfy the need by means of measurement records alone. The single-frequency sensor characteristics noted above in conjunction with aspect angle dependence, target and background configuration (singly and in synergism) and multi-spectral tradeoffs, inexorably lead to a requirement for predictive

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modeling methods. By means of this stratagem, a measured signature data base can be leveraged significantly, improving the fidelity of the overall simulation.

For more than twenty years, the Ballistic Research Laboratory (BRL) has been utilizing solid geometric modeling methods to support vulnerability, lethality and neutron transport studies of military targets.[1-3] In such item-level studies, target geometry and material information are passed to various application codes to derive certain measures-of-performance. Building on the general paradigm, workers at BRL and elsewhere have extended the general techniques to support many predictive signature models[4-6] including optical, millimetre wave (MMW),[†] Infra-Red (IR), magnetic and X-ray models.

It is important to note that this type of analysis must generally be supported by a *solid* geometric model. A solid model[7] is a computer description of closed, solid, three-dimensional shapes represented by an analytical framework within which the three-dimensional material can be completely and unambiguously defined. Two major families of solid model representations exist, each with several unique advantages. The first is the Combinatorial Solid Geometry Representation (CSG-Rep).[8] Solid models of this type are expressed as boolean combinations of primitive solids which are geometric entities described by some set of parameters and occupying a fixed volume in space. The second is the Boundary Representation (B-Rep), of which there are two sub-types: (1) *explicit*, where each solid is described by an explicit enumeration of the extent of the surface of the solid; and (2) *implicit*, where the surface of the solid is described by an analytic function such as a Coons patch, Bezier patch, B-spline, etc. Hybrid systems such as the BRL-CAD Package[9] also exist.

Irrespective of the specific representation used for a three-dimensional geometry and material data base, rarely does an application code read that database directly. Rather, a specific interrogation method is invoked to pass particular geometric and material attributes from a source or reference file to the application code. Clearly the nature of the physics employed in the application is both enabled and constrained by the form of the interrogation process used.

In this paper, several examples of predictive radar codes are given, illustrating several strikingly different ways of linking geometry to applications. Following those examples the interface methods known to the authors will be described. Many of the techniques have already been implemented; some are currently in development. In addition, the utility of various techniques will be related to particular application codes.

2. CASE STUDIES IN PREDICTIVE RADAR MODELING

2.1 Examples of Synthetic Aperture Radar Imagery

Early radars were designed to estimate target range and closing rates. For these systems, the main parameter of interest for a given target was Radar Cross Section (RCS). The RCS figure represents the efficiency with which radar waves are scattered back to the receiver. Certain modern radars, when placed on moving platforms such as aircraft, can be used to form two-dimensional images of targets. Radar imagery of this class is called Synthetic Aperture Radar (SAR). A description of an Armored Fighting Vehicle (AFV) has been analyzed with a SAR program[10] (to be described below) and the results are shown in Figs. 1 and 2.

Figure 1, left-hand side, shows the AFV as seen by the SAR radar from a $(35^\circ, 30^\circ)$ (Azimuth, Elevation) orientation. A horizontal flight path (left to right) is assumed. The properties of SAR processing are such that following signal detection and manipulation an image is derived which resolves the target in range and cross-range (along the flight path) but not in the remaining orthogonal direction. Thus the final SAR image orientation is similar to the optical rendering shown in the right-hand side of Fig. 1.

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† Recently, an initiative was made to consolidate Radar Cross Section (RCS) code development sponsored by the Tri-Services and NASA. *The Electromagnetic Code Consortium* has chosen the geometry tools developed by the BRL as the basis for radar codes to be sponsored by this group. See Ref. 6.
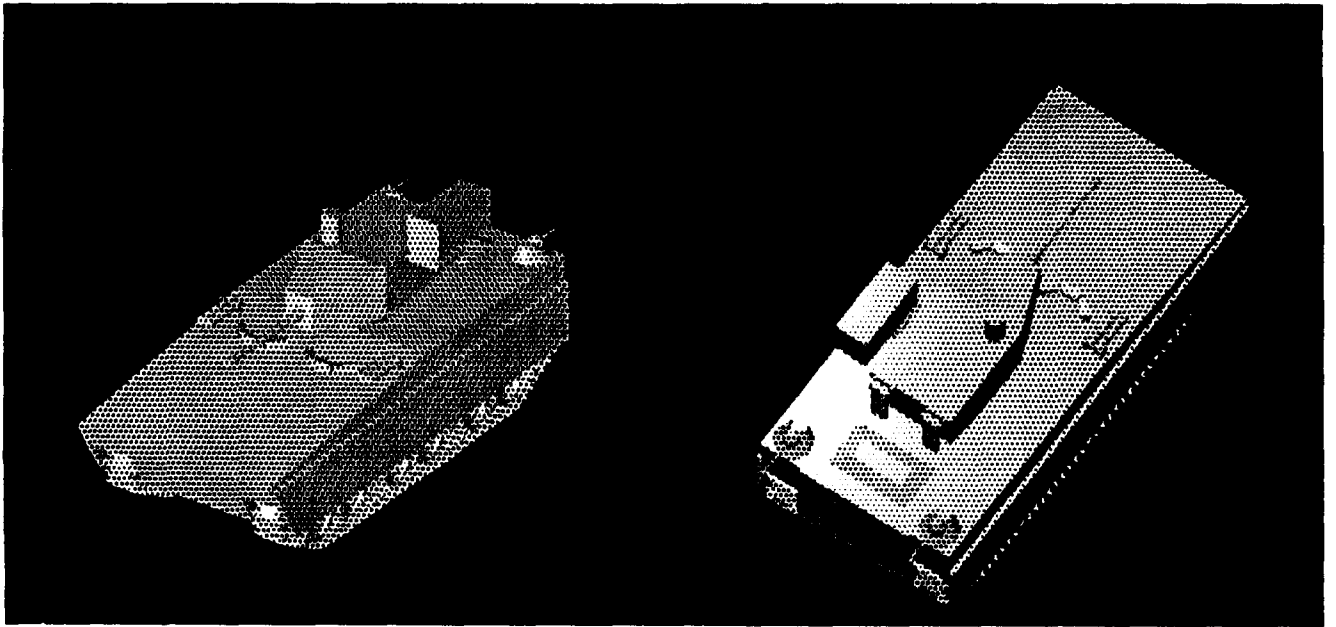
Figure 1. On the left an optical image of an AFV illustrating the radar view of the target $(35°, 30°)$ for a synthetic aperture radar (SAR) simulation. The SAR is modeled as moving in the azimuthal direction (elevation and range constant). On the right, complementary optical image to that shown on the left; the apparent aspect is $(215°, 60°)$ and is suggestive of the SAR reconstructive process when range is plotted against cross-range as in Fig. 2. (From Ref. 10)
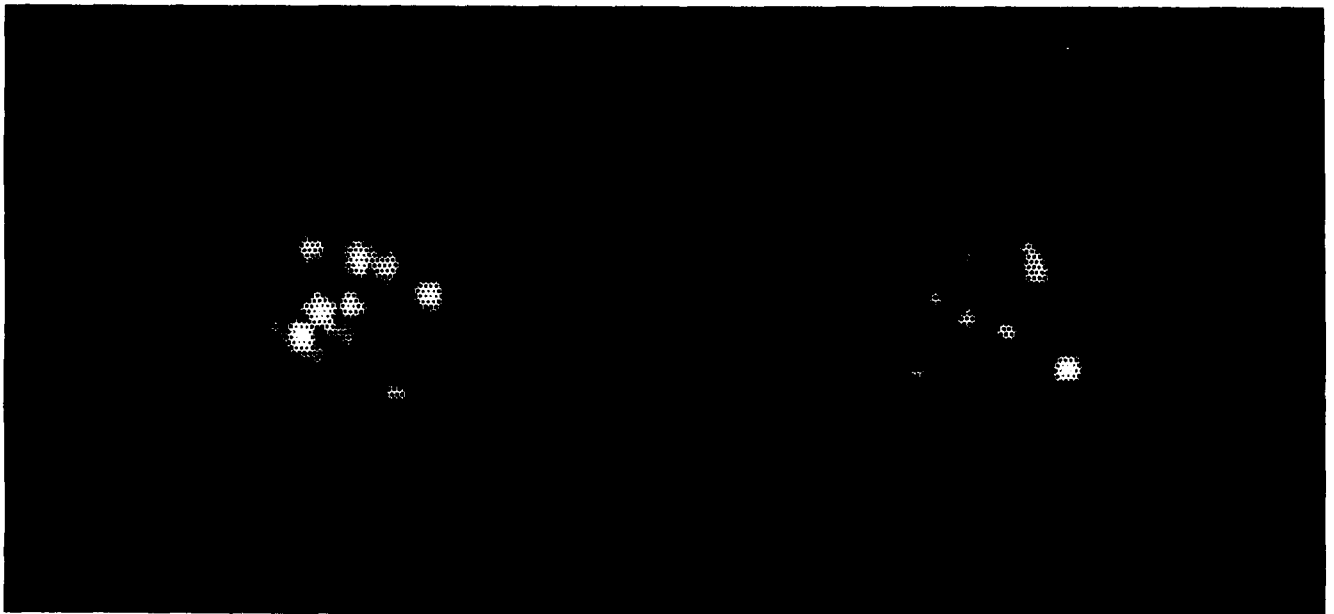
Figure 2. Computed SAR image for target resolution of 10 inches. Left-hand image is for 10 Ghz, Vertical/ Vertical (co-polarization transmit/ receive) modes; right-hand image is for Vertical/ Horizontal (cross-polarization transmit/ receive) modes. (From Ref. 10)

A pair of SAR images for the AFV is shown in Fig. 2. Both images are computed for a target resolution of 10 inches. The left image is the result of a transmit Vertical, receive Vertical polarization mode; the right, for a Vertical/Horizontal polarization mode. In each of these images, the radar signal is propagating from top down. Range information is plotted along the ordinate and cross-range data along the abscissa.

2.2 The SRIM Code of ERIM

Simulated Radar IMagery (**SRIM**) is a high-frequency predictive radar code developed at the Environmental Research Institute of Michigan (**ERIM**).[11] Early versions of the code used a geometry representation scheme for which no convenient editor existed. In 1983, ERIM linked its electromagnetics section of SRIM to BRL's CSG-Rep geometric modeling capability. BRL geometry is described in terms of Boolean combinations (intersections, unions, differences) of primitive objects such as ellipsoids, cylinders, and tori. Ray-tracing is used to extract geometric information from the database. The ERIM-BRL link provides an easy means for generating geometry descriptions through an excellent graphics editor and a natural geometry interrogation technique for determining ray path information. SRIM follows the Geometric Optics (**GO**) paths of rays as they hit and reflect from the target surfaces. For each ray emanating from the radar a piecewise-linear path is traced through the geometry and a history is recorded of hit-point coordinates, normal vectors, principal curvatures, principal curvature directions and a flag designating whether or not line-of-sight exists to the radar. This geometric information is then passed to the electromagnetics portion of the model. At each hit point along the ray path, the incoming illumination wavefront is resolved into parallel and perpendicular components, a complex Physical Optics (**PO**) field contribution at the radar is calculated, taking into account the wavelength of the system and this contribution is then resolved into its vertical and horizontal polarization components. SRIM is thus able to determine the PO field contributions for not only first-surface illumination, but also for contributions due to multiple bounces along the specular directions. If a total radar cross section is desired, this complex return is summed into a total field variable. If a SAR image is desired, the location at which this contribution would appear in an image is calculated and added to the appropriate range/cross-range bin. Image parameters such as resolution, beam weighting and pixel size are specified in a separate file.

If a vehicle on a ground plane is the object of interest, SRIM can generate a clutter model for the ground backscatter and will properly represent the shadowing of the ground plane by the vehicle. In fact, all shadowing effects are correctly represented as a natural result of the ray-tracing paradigm used in this simulation.

2.3 The SARSIM Code of Northrop

SARSIM is another high-frequency synthetic aperture radar simulation code. It was developed at the Northrop Research and Technology Center.[12] In this model, the radar images of the target and surrounding background are computed separately. In a final step the two images are combined *via* processing which reflects appropriate noise, speckle and system-response values. For the geometric calculations an underlying target representation of triangular plates is employed. For a given SAR resolution, each of the triangular plates in the target description is subdivided into panels whose contributions fall into a single SAR resolution bin. For each of these panels in the target description, a PO calculation is carried out to determine the contribution to the corresponding SAR resolution bin. This is also done for a Physical Theory of Diffraction calculation on the panel edges. As of 1987 only the specular (first surface) and diffraction contributions were considered in this model. A simplified shadowing algorithm eliminates any panels partially obscured by other panels. Multiple reflections are not considered yet.

2.4 The TRACK Code of GTRI

Georgia Tech Research Institute (**GTRI**) has developed a radar prediction tool called TRACK.[13] The geometry used by TRACK is based on a subset of objects supported by the GTRI MAX geometry editor. A hybrid representation of simple shapes such as ellipsoids, plates, frusta and special radar-specific constructs such as dihedrals and trihedrals are accepted by the TRACK code. TRACK has a series of subroutines referred to as CROSS which calculate the field contribution of the individual scatterers in a MAX geometry file. CROSS uses PO to calculate the fields for polygonal flat plates, right circular frusta, general ellipsoids, ogives and toroids. A combination of Geometric and Physical Optics is use to calculate the fields for dihedral and trihedral shapes. CROSS also predicts diffraction from straight and curved edges by methods of equivalent currents to avoid problems associated with caustics. The returns from the individual scatterers can be summed coherently,

noncoherently, or retained in complex form for postprocessing. Shadowing is handled by ignoring all plates that face away from the radar and by excluding from the electromagnetics calculations any scatterer that is completely obscured by other geometric elements. When an element is partially covered, the full energy of that element is returned, which can sometimes be a source of error. For post-processing, a file with scatterer types, location, size and orientation is generated. This can then be used in numerous scenarios, such as SAR, doppler radar, and **ISAR** (Inverse **SAR**).

2.5 Discussion of Approaches

Each of the aforementioned high-frequency scattering codes required compromise. The choice of geometric representation and interrogation method led to advantages and shortcomings. Choosing a particular geometric approach often requires approximations in the implementation of the physics of an analysis. Likewise, a particular formulation of a physical analysis can force the acceptance of a simplified and less general geometry representation for the sake of getting some portion of the problem solved.

SRIM uses the information gathered by ray-tracing to determine a scattered field. Fields are calculated locally so that the ray-trace sampling density can be chosen small enough to guarantee that each contribution to the scattered field will lie in a unique resolution cell, a feature not guaranteed by the GTRI model. While the ray-tracing technique is computationally intensive, the automatic shadowing and multiple bounce calculations are attractive features. If two modeled surfaces are at a right angle to each other, the SRIM code will calculate a scattered field that is appropriate for a dihedral without requiring the explicit designation of a dihedral element in the geometry file. This approach does have the severe cost of requiring ray-tracing densities which are frequency dependent, so that the number of rays which must be cast at the target description for a 94 GHz radar calculation is on the order of 100 times the number of rays needed at 10 GHz. Originally the code simply point-sampled the field contribution at a location, but this approach suffered from aliasing problems due to under sampling high spatial frequency (fine detail) geometric elements. Improvements have been made so that the field contribution is integrated over a planar approximation at the scattering surface, so that field calculations are less sensitive to ray-trace sampling densities. Even so, with a ray-tracing approach, one can still run the risk of not adequately sampling the fine detail in the geometric model, although increasing sampling densities with ray-tracing makes the inter-ray sampling distances arbitrarily small. It is possible to place an upper bound on the size of geometric objects that will be under sampled; with knowledge about the distribution of feature sizes in the geometry, the ray spacing can be chosen so as to make it statistically unlikely to miss any details.

Only PO fields are calculated for SRIM. Diffraction effects occurring at edges are not calculated because the ray-tracing interrogation method does not provide the required edge information. Some of the representational schemes discussed later will show how this might be accomplished with an alternate form for extracting information from the model geometry.

One advantage of the SARSIM approach to field calculations is that integration takes place over each facet or panel in a target description and all of the modeled geometry is guaranteed to be included in the calculation. SRIM can not guarantee this. Likewise, if one has adopted a particular resolution cell size and subdivided the triangular plates into panels appropriate for the resolution cell size, there will be no increase in the number of panels for an increase in the frequency of the radar. On the other hand, in modeling the target with flat plates, one must approximate any curved surfaces and thereby introduce some uncertainty about the fidelity of the geometry itself, since flat plate representations of curved surfaces introduce edges where no real edges exist. Thus, each edge must be marked by the geometry modeler, to indicate if the edge is an actual edge, or a modeling artifact. For radar diffraction calculations this criterion must be used to trigger the inclusion or exclusion of edges.

Multiple reflections are not modeled in SARSIM, so any radar signature dominated by multiple bounces of energy within the target will be poorly modeled. Many ground vehicles, especially tracked vehicles, exhibit dramatic dihedral and trihedral returns, making multiple-bounce considerations a primary concern. The use of piecewise-linear target representations does lend itself to polygonal projection for determining multiple path interaction, thereby avoiding ray-tracing. However, such an approach introduces its own set of difficulties. These techniques require significant computation to find all the facet-to-facet "form factors". For a geometry with N facets, a solution to the global illumination problem requires a system of N equations in N unknowns to be solved.

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With most targets of interest the value of N is quite large, and performing Gaussian elimination on the N-by-N matrix is often prohibitive.

The GTRI radar simulation provides highly accurate electromagnetic calculations for most of its primitive geometry types. Of the three models considered here, it provides the most detailed calculations for certain simple objects. For many modeling scenarios this approach gives excellent results. However, the technique for combining these component field calculations for a complex geometric object fails to address some important issues. The basic approach of modeling complex geometry with simple objects for which highly detailed electromagnetic field calculation are known, has been used for many years.[14] For simple shapes, *e.g.* rockets, or for objects where a few scatterers with wide spatial separation dominate the returns, this has been a highly successful technique. When the target under consideration has non-convex complexity such as seen in a tank, the effects of multiple-reflection scattering cannot be ignored. Although the GTRI model has dihedral and trihedral geometric primitives to account for some multiple reflection scattering, the modeler must provide the information of how large and where these objects should be. Even with this feature, multiple reflection paths may escape the modeler's attention or be of such complexity as to be insufficiently modeled by dihedrals or trihedrals. To deal with this type of scattering with a general-purpose code that does not require operator intervention, it would be necessary to appeal to another geometric model of higher resolution to find the multiple reflection paths.

One other shortcoming of this method is the coarseness of the criterion for determining when one primitive obscures or shadows another. The GTRI method does not sufficiently subdivide the scattering geometry, so that full-power returns to the radar are considered to exist even when the scattering object is almost completely obscured. Only when a primitive is totally obscured is the electromagnetic scattering omitted from the field calculation. Notice that even if it were geometrically simple to determine what portion of a given solid is obscured, this electromagnetics calculation method would not provide the field contribution from the partially visible portion. Still worse problems arise for imaging radar simulations if the scattering object is geometrically larger than a resolution cell, since a given scatterer has only one field value and that field value cannot be distributed over more than one cell. This all-or-nothing field calculation method is a consequence of the physics being constrained by the chosen geometry interface.

A geometric representation method and an interface of that method to the scattering calculations have been selected in each of the three codes just discussed. These choices clearly have advantages and liabilities. Any code requiring geometric information will likewise be limited in some areas and enhanced in others by the choices of the geometric representation and the interface of that geometry to the analysis. Each analysis code described so far employs only one of these geometry/analysis code links, but significant benefits might be gained from analysis codes that use two or more of these interfaces simultaneously. Examples of the information that can be readily provided from various geometry representations and interfaces will be discussed in the following sections.

3. GEOMETRIC INTERFACES

In what follows a number of methods are described by which geometric and material data are supplied to applications codes. Where possible, the interface methods developed and supported by the BRL-CAD geometry tools[9,15] will be used to describe and illustrate these processes. A goal of BRL-CAD has been to provide a general and open analysis environment in which a variety of interrogation interfaces are supported so that diverse application codes can be driven from a single, unified geometric model.[16] The **APPENDIX** gives a brief overview of the BRL-CAD modeling environment and some strategies which have guided its development.

3.1 Ray-tracing

Rays begin at a point $\vec{P}$, and proceed infinitely in a given direction given by the unit normal vector $\vec{D}$. The *direction vector* or *direction cosines* for the ray (D_x, D_y, D_z) are the cosines of the angle between the ray and each of the Cartesian axes. Any point $\vec{A}$ on a ray may be expressed as a linear combination of $\vec{P}$ and $\vec{D}$ by the formula

$$\vec{A} = \vec{P} + k * \vec{D}$$

where valid values for k are in the range $[\,0, \infty\,]$.

The traditional approach to ray-tracing has been batch-oriented, with the user defining a set of "viewing angles", initiating a large batch job to compute all the ray intersections and then post-processing all the ray data into some meaningful form. However, the major drawback of this approach is that the application has no immediate control over ray paths, making another batch run necessary for each level of reflection, etc.

In order to be successful, applications need: (1) interactive control of ray paths, to naturally implement reflection, refraction and fragmenting into multiple subsidiary rays and (2) the ability to fire rays in arbitrary directions from arbitrary points. Nearly all non-batch implementations have closely coupled a specific application (typically a model of illumination) with the ray-tracing code, allowing efficient and effective control of the ray paths. The most flexible approach of all is to provide the ray-tracing capability through a general-purpose library and make the functionality available as needed to any application. For example, the decision of when a ray should be reflected, transmitted, or absorbed should be entirely under the control of the application program. A set of sample ray histories that might result from an application exerting such interactive control is shown in Fig. 3.

3.1.1 RT Library Interface: The third generation ray-tracing capability in the BRL-CAD Package is a set of library routines in **librt** to allow application programs to intersect rays with model geometry. There are two parts to the interface: "preparation" routines and the actual ray-tracing routine. **rt_dirbuild()** opens the database file and builds the in-core database table of contents. **rt_gettree()** adds a database sub-tree to the active model space, and can be called multiple times to join different parts of the database together.

To compute the intersection of a ray with the geometry in the active model space, the application must call **rt_shootray()** once for each ray. Ray behaviors such as perspective, reflection, refraction, etc, are entirely determined by the applications program logic, and not by the ray-tracing library. The ray-path specification determined by the applications program is passed as a parameter to **rt_shootray()** in the **application** structure, which contains five major elements: the vector a_ray.r_pt ($\vec{P}$) which is the starting point of the ray, the vector a_ray.r_dir ($\vec{D}$) which is the unit-length direction vector, the pointer *a_hit() to an application-provided routine to be called when some geometry is hit by the ray, the pointer *a_miss() to an application-provided routine to be called when the ray does not hit any geometry, and the variable a_onehit. In addition, there are various locations for applications to store state information such as recursion level, intermediate color values, and cumulative ray distance.

When the a_onehit variable is set to zero, the ray is traced through the entire model. Applications such as lighting models may often only be interested in the first object hit; in this case, a_onehit may be set to the value one to stop ray-tracing as soon as the ray has intersected at least one piece of geometry. Similarly, if only the first three hits are required (such as in the routine that refracts light through glass), then a_onehit may be given the value of three. Then, at most three hit points will be returned, an in-hit, an out-hit and a subsequent in-hit. When only a limited number of intersections are required, the use of this flag can provide a significant savings in run-time.

The **rt_shootray()** function is designed for full recursion so that the application provided a_hit()/a_miss() routines can themselves fire additional rays by recursively calling **rt_shootray()** before deciding their own return value. In addition, the function **rt_shootray()** is fully capable of operating in parallel with other instances of itself in the same address space, allowing the application to take advantage of parallel hardware capabilities where such exist.

3.1.2 Sample RT Application: A simple application program that fires one ray at a model and prints the result is included below, to demonstrate the simplicity of the interface to **librt**.
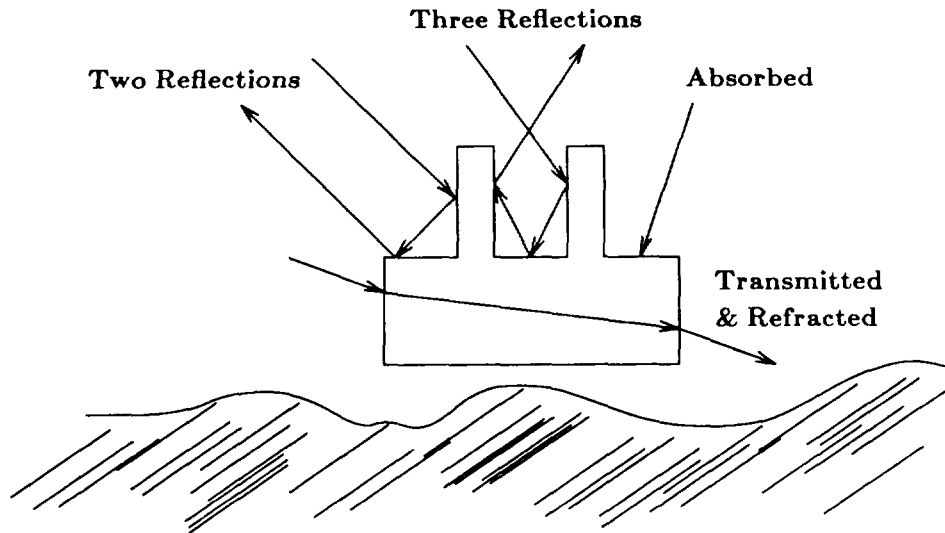
7

Figure 3. Application Control of Multiple Bounces

```
struct application ap;
main() {
    rt_dirbuild("model.g");
    rt_gettree("car");
    rt_prep();
    VSET( ap.a_point, 100, 0, 0 );
    VSET( ap.a_dir, -1, 0, 0 );
    ap.a_hit = &hit_geom;
    ap.a_miss = &miss_geom;
    rt_shootray( &ap );
}
hit_geom(app, part)
struct application *app;
struct partition *part;
{
    printf("Hit %s", part->pt_forw->pt_regionp->reg_name);
}
miss_geom(){
    printf("Missed");
}
```

3.1.3 Ray Intersection Data: If a given ray hits some model geometry, the a_hit() routine is called and is provided a pointer to the head of a doubly-linked list of **partition** structures. Each **partition** structure contains information about a line segment along the ray; the partition has both an "in" (**pt_inhit**) and an "out" (**pt_outhit**) hit point. Each hit point is characterized by the hit distance **hit_dist**, which is the distance k from the starting point **r_pt** along the ray to the hit point. The linked list of **partition** structures is sorted by ascending values of **hit_dist**. As a result of this definition, the "line-of-sight" distance between any two hit points can be determined simply by subtracting the two **hit_dist** values. This will give the distance between the hit points, in millimeters.

If the variable a_onehit was set non-zero, then only the first a_onehit hit points along the partition list are guaranteed to be correct; any additional hit points provided should be ignored. This is usually important only

when a_onehit was set to an odd number; in this case the value of pt_outhit in the last **partition** structure may not be accurate and should be ignored.

If the actual 3-space coordinates of the hit point are required, they can be computed into the **hit_point** element with the C-language version of $\vec{A} = \vec{P} + k * \vec{D}$:

VJOIN1(hitp->hit_point, rayp->r_pt, hitp->hit_dist, rayp->r_dir);

3.1.4 Surface Normals: As an efficiency measure only the hit distances are computed when a ray is intersected with the model geometry. For any hit point, the surface normal at that point can be easily acquired by executing the C macro:

RT_HIT_NORM(hitp, stp, rayp);

In addition to providing the unit-length outward-pointing surface normal in struct **hit** element **hit_normal**, this macro also computes the 3-space coordinates of the hit point in struct **hit** element **hit_point**.

3.1.5 Gaussian Curvature: For any hit point, after the surface normal has been computed, the Gaussian surface curvature at that hit point can be acquired by executing the C macro:

RT_CURVE(curvp, hitp, stp);

At the hit point, there exists exactly one pair of orthogonal directions also orthogonal to the surface normal $\vec{N}$ for which the values of c take on the minimum and maximum values c_1 and c_2. c_1 and c_2 are the inverse radii of curvature and $|c_1| \leq |c_2|$, *i.e.* c_1 is the most nearly flat principle curvature. A positive curvature indicates that the surface bends toward the (outward pointing) normal vector $\vec{N}$ at the hit point. A **curvature** structure has three elements, the unit vector **crv_pdir** (or $\vec{A}$) pointing in the direction of the first principle curvature, the scalar **crv_c1** (or c_1) giving the curvature in the first principle direction and the scalar **crv_c2** (or c_2) giving the curvature in the second principle direction $\vec{B}$. The second principle direction $\vec{B}$ is implied and can be found by taking the cross product of the normal with **crv_pdir**, *i.e.*, $\vec{B} = \vec{N} \times \vec{A}$.

3.1.6 U-V Mapping: Each primitive solid can be considered to be bounded by one or more *regular surfaces*. Each regular surface is defined as the locus of points $\vec{S}(u,v)$ depending on two real parameters u and v which range from 0.0 to 1.0 inclusively. These parameters form the coordinates of a two-dimensional Cartesian u,v-plane. A given (u,v) coordinate will appear only once on each regular surface, but in objects with more than one surface that same (u,v) pair may appear at more than one place on the object. The (u,v) coordinate of the hit point is returned in **uvcoord** structure elements uv_u and uv_v. For any hit point, after the value of **hit_point** has been computed, the (u,v) coordinates of that point can be acquired by executing the C macro:

RT_HIT_UVCOORD(ap, stp, hitp, uvp);

For some simple optical rendering applications , it is sometimes desirable to create a mapping between the coordinate system on the surface of an object to coordinates on a plane. This is generally used to drive simple, two dimensional *texture mapping* algorithms. The most common application is to extract a "paint" color from a rectangular image file at coordinates (u,v), and apply this color to the surface of an object. These parameters can also be used to simulate the effect of minor surface roughness using the *bump mapping* technique. Here, the u and v coordinates index into a rectangular file of perturbation angles; the surface normal returned by RT_HIT_NORM() is then modified by up to ±90 degrees each in both the u and v directions, according to the stored perturbation.

In addition, the approximate "beam coverage" of the ray in terms of the parameters (u,v) is returned in the structure elements uv_du and uv_dv. These approximate values are based upon the ray's initial beam radius (a_rbeam) and beam divergence per millimeter (a_diverge) as specified in the application structure. These delta-u and delta-v values can be helpful for anti-aliasing or filtering areas of the original texture map to produce an "area sample" value for the hit point.

3.2 Topological Representation

Some predictive radar signature codes, such as the TRACK code of GTRI discussed above, do not operate directly on a solid geometric representation of an object. Instead, they rely on the fact that large radar returns occur primarily due to the existence of dihedral and trihedral structures in the object. Rather than describing a vehicle simply as a collection of these topological structures, one can analyze a three dimensional solid model to locate all instances of the topological features of interest. For example, the software could locate planar face elements, edges where two locally planar elements join to make a dihedral, edges where three locally planar elements join to make a trihedral, etc. Then this list of topological features becomes the input to the feature-based analysis code.

Due to the rather broad set of possible interpretations of the term "feature", each kind of topological feature extraction is itself considered an application program and, therefore, is not a standard part of the interrogation library. The process of topological feature extraction is currently programmed using the ray-tracing interrogation features described above.[†]

3.3 3-D Surface Mesh

Combinatorial Solid Geometry (CSG) models are formed by the boolean combination of "primitive" solids.[7] For example, a plate with a hole is most easily modeled as a plate primitive minus a cylinder primitive. It is important that in CSG models, there is no explicit representation of the surfaces of the solids stored; indeed, for complex boolean combinations of complex primitives, some of the resultant shapes may have very convoluted topology and surfaces that may be at best high degree polynomials.

There are many applications that would benefit from being able to express an *approximation* of these complex shapes created using CSG modeling as a collection of planar N-sided polygons (N-gons) which together enclose roughly the same volume of space as the original CSG solid. The most obvious such application is to drive polygon-based rendering routines (lighting modules) for predictive optical signatures. On many modern workstations there is direct hardware or firmware support for high-speed rendering of polygons. In addition, there are whole collections of polygon-based predictive infrared and radar signature programs. Some of the most accurate radar signatures have been calculated using the Method of Moments.[17] This approach requires a three dimensional surface tessellation to sub-wavelength resolution over an entire geometric model.

A sensible strategy for converting a CSG model to the equivalent approximate three dimensional surface mesh is to tackle the problem in two parts. First, a routine has to be written to convert each of the primitive solids into tessellated form. Second, a routine has to be written to take two tessellated objects and combine them according to a boolean operation (union, intersection or subtraction) back into a consistent set of solid tessellated objects. Until very recently, this second step has proven extremely difficult. The topology of solid tessellated objects has traditionally been represented using the "winged-edge" data structure. Within the winged-edge representation, an edge represents the boundary or intersection between exactly two faces. Unfortunately, this structure fails to handle other valid configurations, such as an edge being shared by four faces, or an edge being part of only a single ("dangling") face. These other configurations arise when the topology of an object is not that of a simple 3-manifold, *i.e.* when the topology of the object can not be mapped to a sphere. These non-3-manifold conditions arise in the construction of finite element meshes, and from the use of the boolean intersection operation.

The inability of the winged-edge data structure to represent non-3-manifold configurations resulted in the development of a more general data structure[18,19]. This new data structure has been dubbed alternately the "radial-edge", "Non-Manifold Geometry" (NMG), or "n-Manifold Geometry" data structure. The radial-edge representation provides topological links between *all* faces which share an edge. This single representation has the ability to handle n-manifolds (M^n) for $0 \leq n \leq 3$: 3-manifolds (solid objects), 2-manifolds (lone faces, not part of a solid), 1-manifolds (lone edges, not part of a face) and 0-manifolds (lone points, not part of an edge).

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† See Ref. 5, Figs. 8 and 9.

Consider the intersection of two solids that share only a single face, edge, or vertex. The result of the intersection will be a manifold object of dimension less than three. The winged-edge data structure is unable to represent these boolean results, because it requires every edge to adjoin exactly two faces. Thus, the winged-edge representation is not closed under boolean operations. To overcome this lack of closure, winged-edge systems substitute *regularized boolean operators* which are defined to produce only 3-manifold results; all lesser dimension results are discarded. In contrast, because all manifold objects of dimension less than three can be represented using the NMG data structures, NMG objects are closed under boolean operations.

Employing the NMG representation for faceted solid objects gives rise to the rich set of possibilities diagramed in Fig. 4. From this diagram it should be clear that the final evaluated NMG solid object can be employed in a variety of ways. The primary use will be for input to analysis codes that need an approximate 3-D surface mesh of the solid model. In this case, the NMG objects are sent across the interface, either directly into an application, or *via* a triangulator that turns the planar N-gon faces of the NMG objects into simple triangle lists and thence to applications such as SARSIM. However, a very powerful second use will be to create new faceted shapes which are then stored back in the database as new geometric objects, suitable for future editing or analysis.

While a detailed description of the NMG data structures is beyond the scope of this paper,[20] there are several advantageous properties of the NMGs that are worth mentioning. The NMG representation maintains full topology information, so that the relationships between vertices, edges, loops, faces and shells are continuously available. The geometry information associated with a planar face is the plane equation (which includes the outward-pointing surface normal); the plane equation does not have to be re-derived from the vertices. For applications that would prefer visual realism rather than geometric fidelity, there is room in the vertex geometry structure to carry around a "phony" normal for each vertex, suitable for intensity interpolation shading algorithms used in Gouraud shading,[21] or for normal-vector interpolation shading algorithms.

One of the most exciting current research projects at BRL is the extension of the NMG framework to permit faces either to be planar N-gons, or trimmed Non-Uniform Rational B-Splines ("trimmed **NURBS**"). This will permit many of the tessellation operations to be implemented exactly, rather than as approximations. This will also permit solids to enjoy the economy of having most faces be represented as planar N-gons, which are very compact and efficient to process, while those few faces that require sculptured surface shape control can be represented as trimmed NURBS. This combination provides both efficiency and full shape control in the rich n-manifold topological framework; a combination that does not exist in any current commercial CAD system.

3.4 3-D Volume Mesh

Many forms of energy flow analysis, such as heat flow, vibrational analysis (acoustic energy flow), and stress analysis require the use of 3-D Finite-Element Mesh (**FEM**) techniques. While there has been some work on using the ray-tracing paradigm to construct finite element and finite difference meshes[22] it has been difficult to deal with high spatial frequency (fine detail) portions of the model. In particular, meshing small diameter pipes is problematic; undersampling can cause the pipe to incorrectly be separated into multiple pieces.

In order to improve on the current state of affairs, it seems necessary to provide support for the generation of volume meshes directly as part of the application interface. This would provide the meshing algorithm to have unrestricted access to the underlying geometry, the space partitioning tree, and other internal data in order to perform a better job.

Even more promising still would be a strategy that takes advantage of the NMG support. A first pass might tessellate the model and evaluate the booleans to produce a surface mesh. The second pass would then take the surface mesh and fill the interior (or exterior) volumes with appropriately chosen volume elements. A very good fit could probably be achieved using only parallelepiped ("brick") elements and 20-node "superelements". The brick elements would be used to fill interior volume that does not border on a face, and the superelements would be used for volume that contacts a face. Recourse could be made back to the underlying geometry (perhaps *via* firing a few well chosen rays) to get the curvature of the superelement faces to match the curvature of the underlying primitive, rather than having to rely strictly on the NMG planar-face approximation.
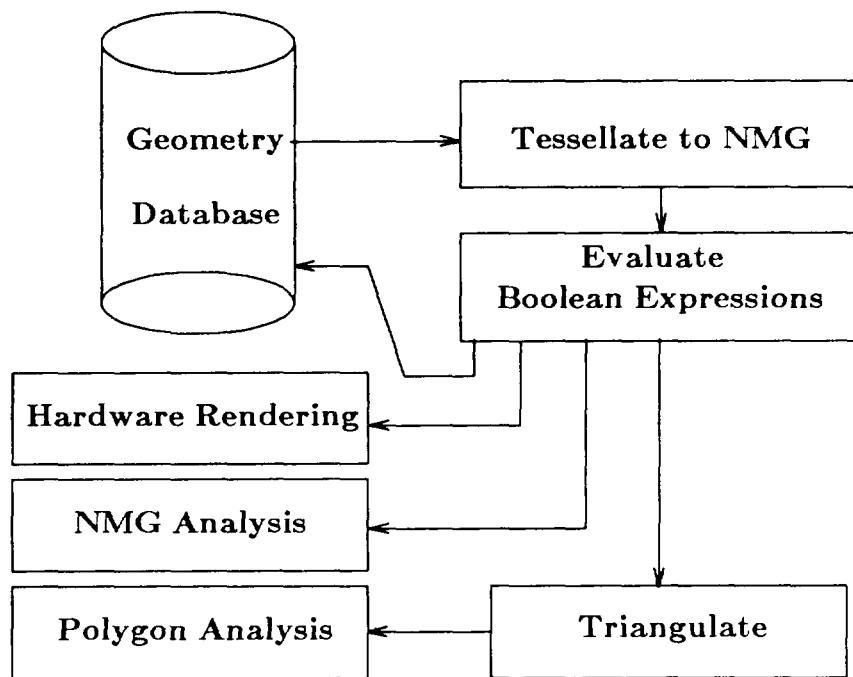
11

Figure 4. Logic flow for n-Manifold Geometry (NMG) processing.

3.5 3-D Volume Elements (Voxels)

A representation which is similar to the finite-element mesh is based on Volume Elements (**VOXELS**). There are two distinct kinds of voxels. The first kind of voxels can be considered a special case of volume meshing discussed previously, in which the model is "diced" into a large collection of homogeneous parallelepiped ("brick") elements. As one example, ERIM has a utility program which uses ray-tracing to convert BRL CSG-format geometry to this kind of voxel representation to feed a first-principles IR model.[23] In contrast to the ERIM's voxel modeling approach, the **Physically Reasonable Infra-Red Signature Model (PRISM)** predictive IR code, developed at the Keweenaw Research Center, is based on a geometry of flat plates.[24] Two codes linking the BRL CSG-format geometry to PRISM have been developed: the TACOM FRED editor[25] and the BRL **irprep** program.[26]

A distinctly different form of voxel representation is based upon the use of 8-way binary space subdivision stored using an "oct-tree" data structure. In this technique, the model is enclosed in a bounding box. The bounding box is evenly split along the X, Y and Z axes to form eight smaller boxes. This algorithm is applied recursively so that all boxes which are neither entirely full nor entirely empty are repeatedly split, until the size of the voxels satisfies some termination condition. In this way, small voxels that lie along the surface of objects can fit arbitrarily tightly to the surface, while the interior of an isomorphic region will be contained primarily in a single large voxel.

The oct-tree representation provides the application program with a homogeneous geometric representation based entirely on cubes of varying size. Having such a homogeneous representation can often greatly ease the task of algorithm development. On the other hand, achieving a good approximation of curved objects using cubes requires a huge number of voxels to be used, resulting in very large voxel datasets, and an exponential increase (order N^6) in the number of element-to-element equations to be solved. The oct-tree approach to IR signature generation is employed in the BRL-CAD program **lgt**.[27]

3.6 Homogeneous Trimmed B-Splines

When support for trimmed NURB faces has been added to the NMG capability, it will be possible to represent all existing primitives either with exact rational B-spline versions, or with very good rational B-spline approximations. This could be done even for faces that were completely planar.

This offers the hope that it might be possible (albeit memory intensive) to convert an entire CSG solid model into a homogeneous collection of non-uniform rational B-spline faces organized in a n-manifold topological data structure. In addition to the conceptual simplicity afforded by having a uniform representation for shape, this affords the opportunity to create new analysis codes that can process curved surfaces, yet at least initially only have to deal with one kind of shape. This would also provide a very direct and natural interface to spline-based and Bezier-patch[28] based modeling systems.

3.7 Analytic Analysis

Given a homogeneous geometric representation such as the Trimmed B-Splines just discussed which also has an analytic representation, a further processing capability arises. Rather than interrogating the data base by means of sampling or subdivision techniques, the direct mathematical manipulation of the source geometry through its parametric representation becomes possible. Calculations of physical properties requiring integration over a surface can often be evaluated with greater accuracy using an explicit analytic calculation than could be provided by numerical methods. While this may be difficult in general due to the complexity of a parametric expression, some classes of surface representations may be good candidates for this approach. Splines, for example, are piecewise-polynomial functions which have relatively simple Fourier transform representations. Since 2-D spatial Fourier transforms arise frequently in far-field electromagnetic scattering calculations, exploitation of the parametric spline form is of interest in predictive scattering calculations. Direct use of spline parameters in a PO scattering model is part of the methodology used at the Aircraft Division of The Northrop Corporation.[29]

Support for this tack may be inferred from the work of Schneider and Peden who have exploited analytic methods for calculation of radar cross sections using dielectric ellipsoids[30] in the detection of buried targets.[31] Here the approach involves the approximation of the geometry of interest with a shape for which the analytic solution of the electromagnetic scattering problem can be solved. Great care must be taken to insure that the errors introduced by the geometry are a small perturbation of the desired solution.

With the rapidly developing potential of symbolic calculation, treatment of seemingly impossible formulas resulting from the geometry/physics interaction may become tenable. This could help to reduce the trend towards employing numerical methods at the onset of a problem and avoid some of the accompanying instabilities and errors.

4. SUMMARY

In this paper we have discussed some issues basic to the prediction of signatures in support of Automatic Object Recognition, in particular the way in which three-dimensional geometry and material data are linked to certain applications. This point was illustrated *via* a discussion of three predictive radar codes, each designed for essentially the same application, but each nevertheless employing unique geometric methods. The descriptive approach and the manner in which each is linked to the physics of the codes has been shown to both enable and constrain algorithmic exploitation.

The methods for linking geometry to applications codes were described in turn. The BRL-CAD package was used to illustrate each approach. As described in the **APPENDIX**, the strategy utilized in BRL-CAD is based on an inhomogeneous collection of closed-surface geometries, of which the variety of shapes is constantly expanding. By this tack, in addition to using geometry files created with BRL-CAD, three-dimensional geometry files that were developed under other systems can either be mapped into the BRL-CAD data base *exactly* (if the corresponding geometric forms already exist) or the data base can be extended to support any important new forms (so that the conversion becomes an exact mapping as well). By this method the enormous costs of geometry generation can be

recovered; any model developed on a true 3-D modeling system can be transferred through file importation to the general and open environment of BRL-CAD.[‡]

Another important point that was emphasized was the possible utility of each particular interface. A related goal, therefore, of BRL-CAD has been to support *all* such interfaces from the extensible data base of geometry types. Many of the forms have been implemented; the NMGs which will provide homogeneous polygon support are in the final stages of development.

By these developments it is our intent to support the AOR community to the maximum extent possible with the tools needed to develop the multi-spectral, multi-sensor simulations critical to autonomous-sensor applications.

APPENDIX

The solid modeling package called BRL-CAD[9,15] was originally developed to support the input requirements of vulnerability and lethality modeling at the Ballistic Research Laboratory. Its capabilities are briefly summarized here:

- BRL-CAD is composed of more than 200,000 lines of portable C language source code which support:
  □ Solid geometric editor (mged)
  □ Ray tracing utilities
  □ Lighting models for a variety of frequencies
  □ Many image-handling, data-comparison, image-processing and other supporting utilities

- The set of closed-surface (inhomogeneous) geometrical representations supported by BRL-CAD include:
  □ The original Constructive Solid Geometry (CSG) BRL data base
  □ Non-Uniform Rational B-Spline Surfaces (NURBs)
  □ The faceted data representation (PATCH) developed by Falcon/ Denver Research Institute and used by the Navy and Air Force for vulnerability calculations.

- It supports association of material (and other attribute properties) with geometry which is critical to subsequent applications codes.

- It supports a set of extensible interfaces by means of which geometry (and attribute data) are passed to applications:
  □ Ray casting
  □ Topological representation
  □ 3-D Surface Mesh Generation
  □ 3-D Volume Mesh Generation
  □ Analytic (Homogeneous Spline) representation

- Source code for BRL-CAD has been distributed to more than 650 computer sites world wide throughout Government, Industry and Academia.

- In addition to the vulnerability and signature codes generated by the BRL, many BRL-CAD based applications codes have been built by others, including applications developed by workers at TACOM/ Keweenaw Research Center, ERIM, Northrop, MITRE, University of Illinois and scores of other sites.

Figure A1 gives a general layout of the BRL-CAD database representation. A number of fundamental strategies are key here. First, the primary data base is inhomogeneous; that is, many types of geometric representations are allowed so long as they represent fully enclosed space. New shapes are added to the geometric

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‡   An important caveat here is that the mathematical form of the geometric representation and data base to be imported must be known. Unfortunately, most commercial CAD vendors are unwilling to provide this information for files generated by their systems, since that might *free the user from "vendor lockin"*.
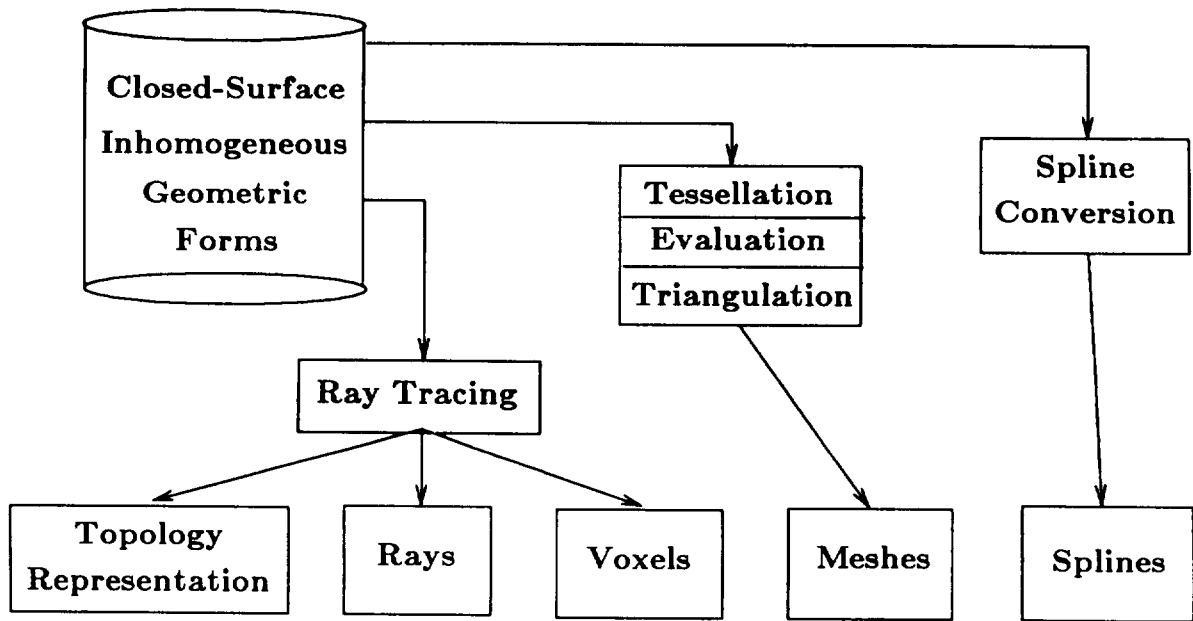
Figure A1. Organization of BRL-CAD Database Representation.
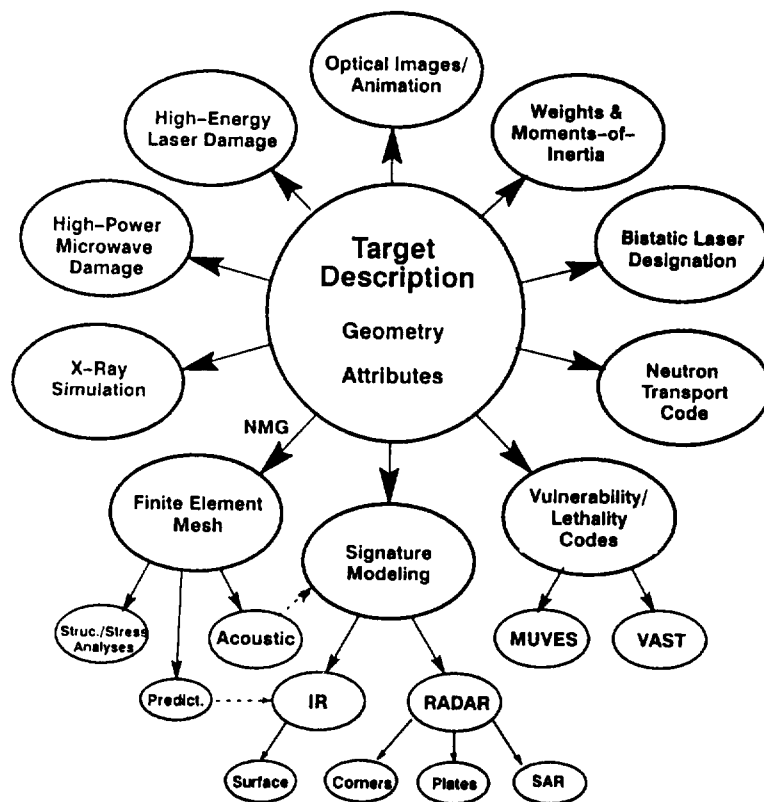
Figure A2. Current Applications of BRL-CAD.[1-7,10,15]

15

data base from time to time and the BRL-CAD package has a number of utilities written expressly to aid that process.

Second, specific interface standards have been adopted at the points where geometry is normally passed to applications (*e.g.* ray casting, topology, surface mesh). By this strategy changes which take place in the geometric data base itself are isolated from the specific means of geometry linkage. By means of this strategy both (a) an extremely large primary data base of geometry types can be supported in a data-storage efficient fashion and (b) various application codes can link to that data base in the manner most suitable for the application.

As noted above, although the original application of BRL-CAD was in support of vulnerability and lethality analyses, its utility has been extended much beyond those applications.[1-7,10,15] A graphical depiction of current uses is given in Fig. A2.

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