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ACME Algorithms for Contact in a Multiphysics Environment API Version 1.0

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ACME
Algorithms for Contact in a Multiphysics Environment
API Version 1.0

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Abstract

An effort is underway at Sandia National Laboratories to develop a library of algorithms to search for potential interactions between surfaces represented by analytic and discretized topological entities. This effort is also developing algorithms to determine forces due to these interactions for transient dynamics applications. This document describes the Application Programming Interface (API) for the ACME (Algorithms for Contact in a Multiphysics Environment) library.

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1. Introduction

Contact algorithms play an important role in many research and production codes that simulate various interfacial aspects of continuum solid and fluid mechanics and energy transport. Because of the difficult nature of contact in general and in order to concentrate and leverage development efforts, an effort is underway at Sandia National Laboratories to develop a library of algorithms to search for potential interactions between surfaces represented by finite element meshes and other topological entities. The requirements for such a library, along with other pertinent information, are documented at the following World Wide Web site:

```
http://www.jal.sandia.gov/SEACAS/contact/index.html
```

This document describes the Application Programming Interface (API) for the ACME search and transient dynamics enforcement library. (In an attempt to avoid confusion, capitalized terms are used in this document to refer to specific terminology for which detailed definitions are provided. A glossary of these terms is given in Appendix A.) This introductory section gives an overview of the concepts and design of the ACME interface and outlines the building blocks that make up the data ACME needs from the host code and the data it returns to the host code. Section 2 describes various utility functions used to extract information about the package and its operation. Section 3 describes the functions needed to access and utilize the search capabilities of ACME. Section 4 describes functions that can be used to remove an initial overlap for a mesh prior to beginning a transient. Section 5 describes the functions provided by ACME to enforce the results of the search to explicit transient dynamics. Finally, Section 6 provides an example of how to use the API within a C++ application.

The basic philosophy of the ACME interface is to provide a separate function to support each activity. Efforts have been made to have the C++, C, and Fortran interfaces appear as similar as possible. It is important to note that all array indexes will use the Fortran convention (i.e., indexes start with 1) and all floating-point data are double precision.

This release of the ACME library contains only a subset of the algorithms and functionality required to meet all the needs of the application codes. Currently, ACME supports three-dimensional (3D) topologies in serial and in parallel processing modes. No multi-state support is provided in this release (i.e., ACME has no ability to revert to previous states). ACME only supports conventional nodes (shell nodes and smooth particle hydrodynamics nodes are not yet supported) and a limited set of face types (a linear 4-node quadrilateral, a quadratic 8-node quadrilateral, a linear 3-node triangle, and a quadratic 6-node triangle) in this release. Additional algorithms and functionality will be added in subsequent releases.

1.1 Topology

The topology for ACME is determined by the host code. The first step in using the library is for the host code to provide to ACME a topological description of the surfaces to be checked for interactions. Currently, the topology consists of collections of nodes, faces, and analytic surfaces. Nodes and faces are supplied to ACME in groups called blocks. A Node_Block may contain only one type of node. A Face_Block may contain only one type of face and all faces will have the same Entity_Key (Entity_Keys are used to extract user-specified parameters from the Search_Data array for pairs of interacting topological entities, as explained in Section 1.1.4). Providing the full functionality required of ACME will necessitate adding Edge_Blocks and Element_Blocks. When added, these items will be analogous to the Face_Blocks (see the description in Section 1.1.2). Also, the full functionality required of ACME will necessitate adding multiple states; for this initial release of ACME, only a single state (with one or two configurations) will be supported.

1.1.1 Node_Blocks

A Node_Block is a collection of nodes of the same type. Currently, the only type of node supported in ACME is a conventional node that has a position attribute and an optional projection direction attribute (for face/face search; see Section 1.3.3). Eventually three types of nodes will be supported:

NODE: A traditional node with position and an optional projection direction attribute.

NODE_WITH_SLOPE: A shell node that has a first derivative as an attribute and an optional projection direction attribute.

NODE_WITH_RADIUS: A node that has a radius as an attribute and an optional projection direction attribute. This radius is associated with the size of a spherical domain, as with smooth particle hydrodynamics (SPH) particles.

In this release only NODE Node_Blocks are supported. All of the nodes that are connected to faces must be in the first Node_Block. Other Node_Blocks can be used for nodes not connected to faces in the ContactSearch topology. These additional Node_Blocks can be used for SPH particles (neglecting the radius of the particle) or for finding the Gauss point locations on the other side of an interface. The implication for requiring all nodes connected to faces be in Node_Block 1 is that the nodal communication lists only refer to nodes in Node_Block 1.

Each Node_Block is assigned an integer identifier (ID). This ID corresponds to the order the blocks were specified, using the Fortran numbering convention (i.e., the first block has an ID of 1, the second block has an ID of 2, etc.). This ID is used in specifying configurations for Node_Blocks and for returning NodeFace_Interactions and NodeSurface_Interactions, discussed later in Section 1.3.

1.1.2 Face_Blocks

A Face_Block is a collection of faces of the same type that have the same Entity_Key (Entity_Keys are used to extract user-specified parameters from the Search_Data array, as explained in Section 1.1.4). Currently, a linear 4-node quadrilateral face called QUADFACEL4, a quadratic 8-node quadrilateral face called QUADFACEQ8, a linear 3-node triangular face called TRIFACEL3, and a quadratic 6-node triangular face called TRIFACEQ6 are supported. Other face types will be added as needed. These are provided in an enumeration in the ContactSearch header file:

```
enum ContactFace_Type {
      QUADFACEL4 = 1,
      QUADFACEQ8,
      TRIFACEL3,
      TRIFACEQ6 }
```

Each Face_Block is assigned an ID. This ID corresponds to the order the blocks were specified, in the same manner IDs were assigned to Node_Blocks. This ID is used in returning NodeFace_Interactions.

1.1.3 Analytic_Surfaces

In many instances, it is advantageous to search for interactions against rigid analytic surfaces (referred to as Analytic_Surfaces throughout this document) rather than mesh such a surface. Examples include a tire rolling on a flat road or dropping a shipping container on a post. Currently, ACME is designed to handle only geometric analytic surfaces (e.g., planes, cylinders, etc.), and for now, only planar, spherical and cylindrical Analytic_Surfaces are supported. Other geometric Analytic_Surfaces will be added in the future as needed. Eventually, Analytic_Surfaces defined by Non-Uniform Rational B-Splines (NURBS) will be supported. The ACME API will need to be extended to support Analytic_Surfaces defined by NURBS.

Analytic_Surfaces, if any, are provided by the host code to ACME after the Node_Blocks and Face_Blocks have been specified. Analytic_Surfaces are given an ID that corresponds to the total number of Face_Blocks plus the order the Analytic_Surface was added (e.g., if three Face_Blocks exist in the topology, the ID of the first Analytic_Surface is 4, the ID of the second Analytic_Surface is 5, etc.). This ID is used in returning NodeSurface_Interactions.

1.1.4 Search_Data

The Search_Data array contains data that describe how the various topological entities are allowed to interact. The host code may specify, for example, that only nodes on surface A interact with faces on surface B, or that only nodes on surface B interact with faces on surface A, or both. The Search_Data array is the only place where such user-specified data are kept.

Currently the Search_Data array holds only three parameters for each Entity_Key pair. The first parameter is a status flag indicating what type of interactions should be defined for this pair. Seven values are currently permitted, provided in an enumeration in the ContactSearch header file:

```
enum Search_Interaction_Type{
      NO_INTERACTION = 0,
      SLIDING_INTERACTION,
      TIED_INTERACTION,
      FACE_FACE_INTERACTION,
      FACE_COVERACE_INTERACTION,
      NFI_AND_FFI,
            NFI_AND_FCI};
```

NO_INTERACTION (a value of 0) requests that no interactions be defined for this pair of entities. SLIDING_INTERACTION (a value of 1) requests that ACME search for new node/face or node/surface interactions between entities each time a search is executed. TIED_INTERACTION (a value of 2) requests that a node/face or node/surface interaction between entities persist over multiple time steps, thus allowing it to be used for mesh tying. FACE_FACE_INTERACTION (a value of 3) requests that ACME search for new face/face interactions between entities each time a search is executed. FACE_COVERAGE_INTERACTION (a value of 4) requests that ACME search for new face/coverage interactions between entities each time a search is executed. In addition, it requires that a face/face search also be performed. NFI_AND_FFI (a value of 5) requests that ACME search for new node/face or node/surface interactions and face/face interactions between entities each time a search is executed. NFI_AND_FCI (a value of 6) requests that ACME search for new node/face or node/surface interactions and face/coverage interactions between entities each time a search is executed. In addition, it requires that a face/face search also be performed

The second parameter in the Search_Data array is the Search_Normal_Tolerance, which is used to determine whether the entity pair should interact, based on the separation between the entities (see Figure 1). Note that the Search_Normal_Tolerance is an absolute distance, so it is dependent on the units of the problem. The third parameter is the Search_Tangential_Tolerance, also used to determine whether the entity pair should interact, but taking into account distances tangential to a face, rather than normal to it.

Every face and node is assigned an Entity_Key to allow retrieval of data from the Search_Data array. For faces, the Entity_Key corresponds to the Face_Block ID. Currently, a node inherits its Entity_Key from the first face that contains it. This is a limitation of the current implementation, since a node can be connected to two or more faces that are in different Face_Blocks.

The Search_Data array is a three-dimensional Fortran array with the following size

```
     dimension search_data(3,num_entity_keys,num_entity_keys)
```

The first index represents one of the three parameters described previously for each entity pair, currently either a node-face or a node-Analytic_Surface pair. The second index indicates the Entity_Key for the node in an interaction, and the third index indicates the Entity_Key for the face or Analytic_Surface in an interaction.

1.2 Search Algorithms

ACME provides three different algorithms for determining interactions. The data types returned in the interactions are the same for each type of search. The host code may use different types of search algorithms during an analysis (e.g., a static 1-configuration search to determine overlaps in the mesh before starting the analysis and then a dynamic search once time stepping begins in a transient dynamics code).

As an aid to understanding the differences between the search algorithms, consider the idealized 2D face of Figure 1. In this idealized example, the subtleties of what happens at the edge of a face are ignored. Any entity that is outside the face, where “outside” is defined by the outward unit normal **n**, is not penetrating and has a positive Gap. Any entity that is on the face (i.e., a zero Gap) or inside the face (i.e., a negative Gap) is considered to be penetrating. The host code controls the Search_Normal_Tolerance as part of the Search_Data array (see Section 1.1.4). The Motion_Tolerance accounts for movement of the node if two configurations are used and is computed by ACME.

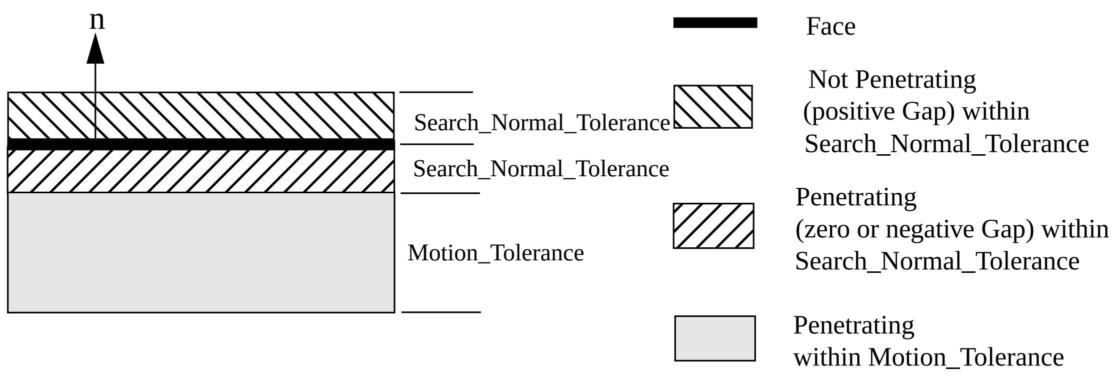

n
Search_Normal_Tolerance
Search_Normal_Tolerance
Motion_Tolerance
Face
Not Penetrating (positive Gap) within Search_Normal_Tolerance
Penetrating (zero or negative Gap) within Search_Normal_Tolerance
Penetrating within Motion_Tolerance

Figure 1 Idealized 2D face with Search_Normal_Tolerance

A separate tolerance, Search_Tangential_Tolerance, is used to specify the behavior of the search algorithms along the edge of a face. As shown in Figure 2, a NodeFace_Interaction will be defined for any node that is outside the face tangentially but within the Search_Tangential_Tolerance. The host code controls the Search_Tangential_Tolerance as part of the Search_Data array (see Section 1.1.4).

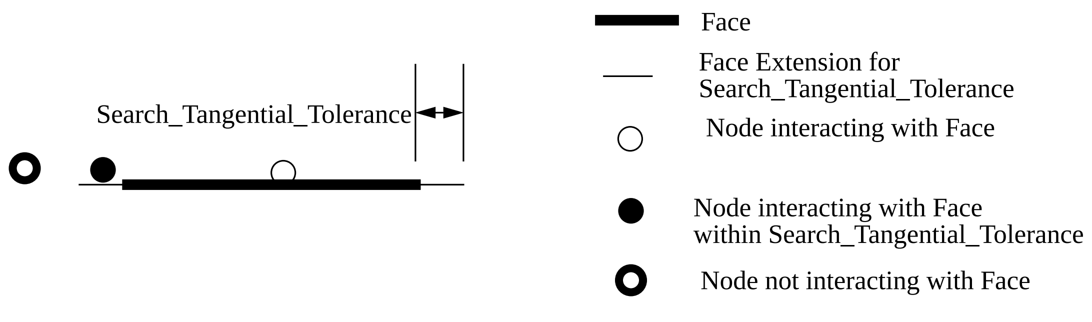

Search_Tangential_Tolerance
Face
Face Extension for Search_Tangential_Tolerance
Node interacting with Face
Node interacting with Face within Search_Tangential_Tolerance
Node not interacting with Face

Figure 2 Idealized 2D face with Search_Tangential_Tolerance

1.2.1 Static 1-Configuration Search Algorithm

The static 1-configuration search algorithm uses only one configuration for the topology. The interactions are determined using only a closest point projection algorithm. Interactions are defined only for entities that are within the Search_Normal_Tolerance (either negative or positive Gap) and the Search_Tangential_Tolerance since the Motion_Tolerance is implied to be zero.

1.2.2 Static 2-Configuration Search Algorithm

The static 2-configuration search algorithm requires two configurations (Current and Predicted) for the topology. This search algorithm uses closest point projection on the predicted configuration but it has the added information of the movement of the topology. The motion tolerance implied by the two configurations is used along with the Search_Data to determine what interactions are physically realistic. Specifically, any node that has a positive Gap within the Search_Normal_Tolerance or any node that has a negative Gap within the Search_Normal_Tolerance plus the motion tolerance will result in an interaction being defined, provided that the node's projection falls within the face boundary as extended laterally by the Search_Tangential_Tolerance.

1.2.3 Dynamic 2-Configuration Search Algorithm

The dynamic 2-configuration search algorithm also requires two configurations (Current and Predicted) for the topology. A dynamic intersection algorithm based on linear interpolation of the motion is used to initiate interaction if the current and predicted Gaps are on opposing sides of the face (e.g., the current configuration has a positive Gap and the predicted configuration has a negative Gap). A closest point projection algorithm is used for subsequent interaction definition and to initiate interaction if the current and predicted Gaps are on the same side of the face. In these cases, interactions are defined by the same criteria as in the static 2-configuration search algorithm (see Figure 1).

1.2.4 Dynamic Augmented 2-Configuration Search Algorithm

The dynamic augmented 2-configuration search algorithm is a more accurate implementation of the dynamic 2-configuration search algorithm. This search can only be used in conjunction with the ContactTDEnforcement enforcement algorithm. It uses information from the enforcement on the previous step to compute an augmented configuration that yields more accurate interactions.

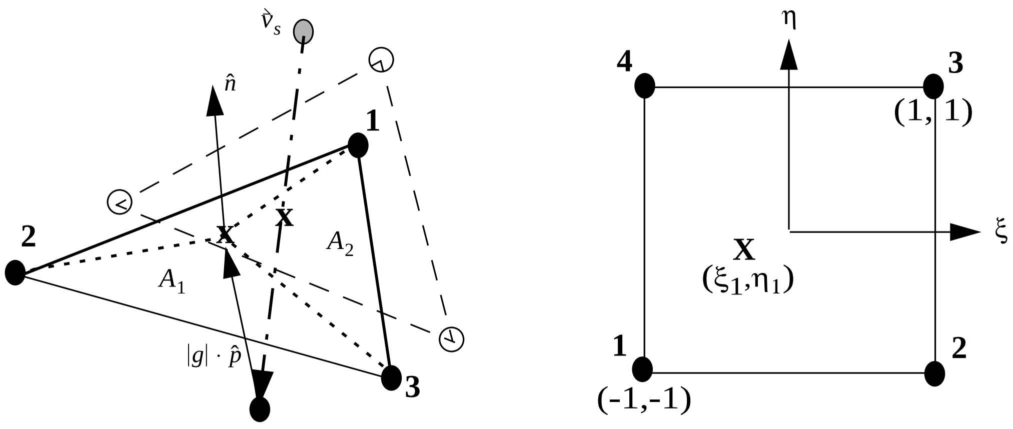
1.3 Interactions

The output of ACME following a search is a collection of interactions based on the topology, configuration(s), Search_Data, and search algorithm. Currently, four types of interactions are supported: NodeFace_Interactions, NodeSurface_Interactions, FaceFace_Interactions and FaceCoverage_Interactions. ACME does not determine the *best* interaction between these types (i.e., ACME does not compete a NodeFace_Interaction against a NodeSurface_Interaction when the same node is involved;

both are returned to the host code). Other interaction types (e.g., EdgeFace_Interaction) will be added in the future. The FaceFace_Interactions and FaceCoverage_Interactions are only available in the static 1-configuration search.

1.3.1 NodeFace_Interactions

A NodeFace_Interaction is returned as a set of data to the host code: a node (indicated by the Node_Block ID and the index in that Node_Block), a face (indicated by the Face_Block ID and the index in that Face_Block) and data describing the interaction. Consider the examples shown in Figure 3. The first diagram illustrates an interaction defined using the dynamic intersection algorithm. Here, a node, lightly shaded in its current configuration and black in its predicted configuration, intersects a TRIFACEL3 at **X** in an intermediate configuration denoted with white nodes. The motion of the node is represented by the vector v_s. Also shown are the data that are returned for this interaction. Specifically, the pushback direction is given by the vector from the penetrating node's predicted position to the position of the contact point convected into the predicted configuration. In the second diagram, the contact point **X**, determined by closest point projection for a single configuration, is shown in local coordinate space for a QUADFACEL4. Table 1 gives the Fortran layout of how the data are returned. It should be noted that only two local coordinates are returned. For triangular faces, the third local coordinate is simply unity minus the sum of the other two local coordinates.



Local Coordinates: (of contact point **X**)	$\xi_1 = \frac{A_1}{A_T}$, $\xi_2 = \frac{A_2}{A_T}$, $\xi_3 = \frac{A_3}{A_T}$	Local Coordinates: (of contact point **X**)	$\xi_1 = \xi_1$, $\xi_2 = \eta_1$
Gap:	g (not returned)	Gap:	g (not shown)
Unit Pushback Vector:	$\hat{p}$	Unit Pushback Vector:	$\hat{p}$ (not shown)
Unit Surface Normal:	$\hat{n}$	Unit Surface Normal:	$\hat{n}$ (not shown)
Algorithm:	Dynamic Intersection	Algorithm:	Closest Point Projection (1-Configuration)

Figure 3 3D NodeFace_Interactions

Table 1 NodeFace_Interaction Data for 3D

Location (Fortran Indexing)	Quantity
1	Local Coordinate 1 (ξ_1 for Q4 or Q8, ξ_1 for T3 or T6)
2	Local Coordinate 2 (η_1 for Q4 or Q8, ξ_2 for T3 or T6)
3	Gap
4-6	Unit Pushback Vector (x, y & z components)
7-9	Unit Surface Normal (x, y & z components)
10	Algorithm Used to Define Interaction {1=Closest Point Projection (1 Configuration), 2=Closest Point Projection (2 Configuration), 3=Dynamic Intersection (2 Configuration)}

1.3.2 NodeSurface_Interactions

A NodeSurface_Interaction is returned as a set of data: a node (indicated by the Node_Block ID and the index in that Node_Block), an Analytic_Surface (indicated by its ID) and the data describing the interaction. Figure 4 shows the interaction data that are returned to the host code for each interaction. Table 2 gives the layout for the data for a NodeSurface_Interaction.

For this release of ACME, NodeSurface_Interactions are determined using a closest point projection algorithm. Therefore, only one configuration is required for the Analytic_Surfaces. The configuration used for the nodes is based on the current configuration for a 1-configuration static search and the predicted configuration for the 2-configuration static search or the dynamic searches. This limitation will be removed in a future release.

Table 2 NodeSurface_Interaction Data for 3D

Location (Fortran Indexing)	Quantity
1-3	Interaction Point (x, y & z coordinates)
4	Gap
5-7	Unit Surface Normal (x, y & z components)

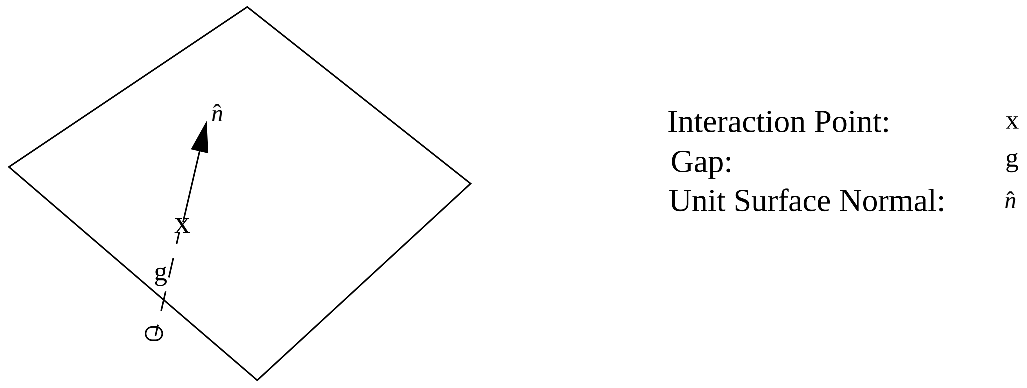
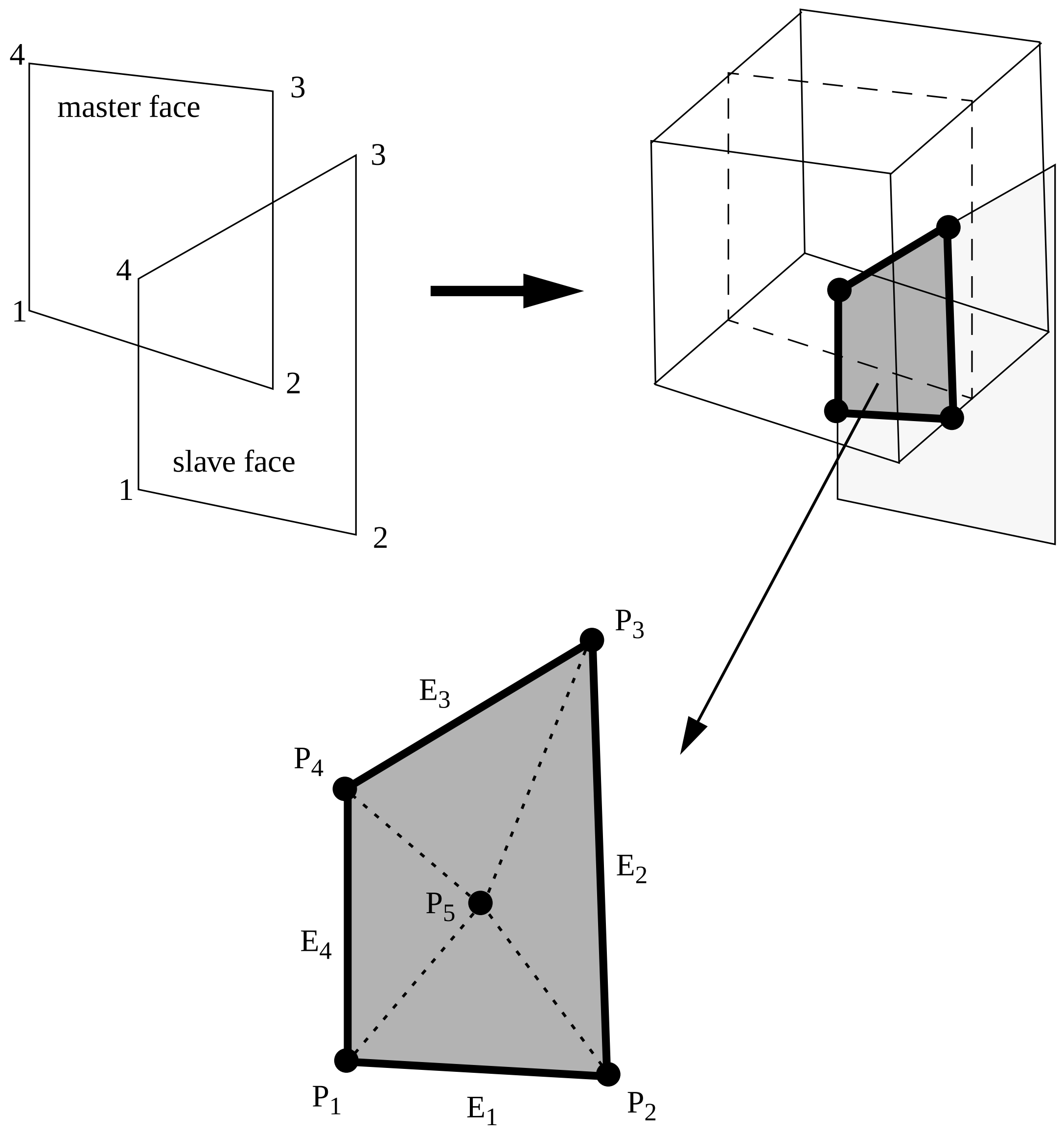


Figure 4 3D NodeSurface_Interaction Data

1.3.3 FaceFace_Interactions

A FaceFace_Interaction is returned as a set of data to the host code: a slave face (indicated by the Face_Block ID and the index in that Face_Block), a master face (indicated by the Face_Block ID and the index in that Face_Block), and data describing the interaction. This interaction is only valid for faces of type QUADFACEL4 and TRIFACEL3. Consider the example shown in Figure 5. Here, two faces are in proximity and the FaceFace_Interaction needs to be determined. The master face is transformed into a master volume by projecting the nodes in the +/- projection direction by the Search_Normal_Tolerance. By default, the projection direction for each node on the master face is the normal at that node (with or without smoothing). Optionally, the projection direction can be user-specified as a node attribute. This permits “mortarising” to be performed under user control (see Figure 6). Once the master face has been converted to a master volume, the intersection between the slave face and master volume is computed. This intersection is described with a closed polygon having N sides, E_n, and nodes, P_n. The points on the slave face that define the polygon are stored in the local coordinates of the slave face. These points are also computed as local coordinates of the master volume and projected onto the master face by setting $\xi_3 = 0$ and then stored in the local coordinates of the master face. The resulting convex polygon can be triangularized by the host by calculating the centroid of the polygon, P_{N+1}, and connecting it to each node. Two additional arrays (of length N) are defined that indicate with which edge, if any, of the master or slave face an edge of the polygon is coincident. Table 3 gives the Fortran layout of how the data are returned. It should be noted that only two local coordinates are returned. For triangular faces, the third local coordinate is simply unity minus the sum of the other two local coordinates.



Number of edges	= 4
Master edge flag array	= [0, 0, 0, 0]
Slave edge flag array	= [0, 0, 3, 4]
Polygon nodes	= P_1, P_2, P_3, and P_4
Polygon centroid	= P_5

Figure 5 3D FaceFace_Interactions

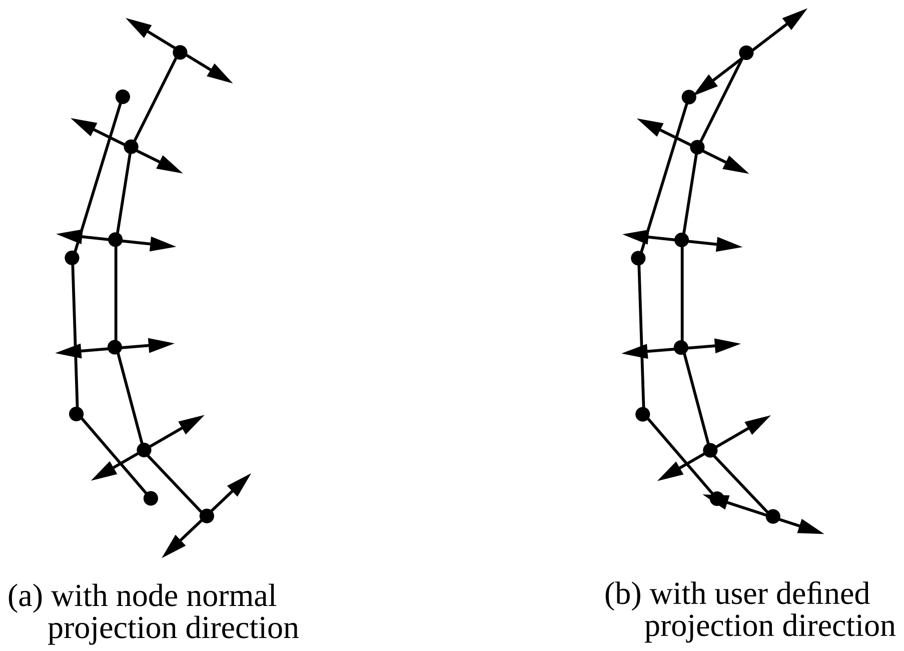

(a) with node normal projection direction
(b) with user defined projection direction

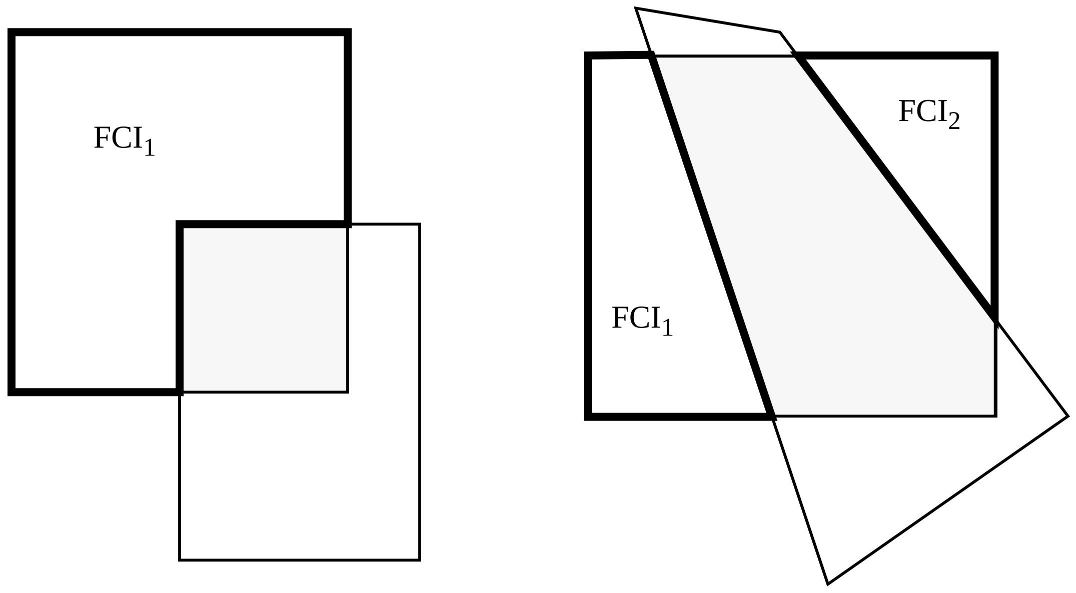
Figure 6 2D example of using PROJECTION_DIRECTION attribute to obtain user defined mortarising.

Table 3 FaceFace_Interaction Data for 3D

Location (Fortran Indexing)	Quantity
1	number of vertexes (and edges), N
1+n	slave edge flag for edge n=1,...,N
(N+1)+n	master edge flag for edge n=1,...,N
(2*N+1)+4*(n-1)+1	Local Coordinate 1 on slave face for polygon node X_n, n=1,...,N
(2*N+1)+4*(n-1)+2	Local Coordinate 2 on slave face for polygon node X_n, n=1,...,N
(2*N+1)+4*(n-1)+3	Local Coordinate 1 on master face for polygon node X_n, n=1,...,N
(2*N+1)+4*(n-1)+4	Local Coordinate 2 on master face for polygon node X_n, n=1,...,N

1.3.4 FaceCoverage_Interactions

A FaceCoverage_Interaction is returned as a set of data to the host code: a face (indicated by the Face_Block ID and the index in that Face_Block) and data describing the interaction. Each FaceCoverage_Interaction is a closed polygon that describes an exposed (i.e., uncovered) portion of a face. The FaceCoverage_Interaction is computed by post-processing the FaceFace_Interactions for each face. A directed edge graph is constructed using the edges of the polygon from all the FaceFace_Interactions associated with each face and any portions of each face edge that are not part of a FaceFace_Interaction polygon. Closed polygons are then extracted from the directed edge graph to produce one or more FaceCoverage_Interactions for each face, as shown in Figure 7 . Table 4 gives the Fortran layout of how the data are returned. For triangular faces, the third local coordinate is simply unity minus the sum of the other two local coordinates.



(a) One FaceCoverage_Interaction produced from post-processing the FaceFace_Interactions.

(b) Two FaceCoverage_Interactions produced from post-processing the FaceFace_Interactions.

▢	FaceFace_Interaction Polygon
▬	FaceCoverage_Interaction Polygon Edge

Figure 7 Post-processing of FaceFace_Interactions to produce FaceCoverage_Interactions.

Table 4 FaceCoverage_Interaction Data for 3D

Location (Fortran Indexing)	Quantity
1	Number of vertexes (and edges), N
2*(n-1)+2	Local Coordinate 1 for polygon node P_n, n=1,...,N
2*(n-1)+3	Local Coordinate 2for polygon node P_n, n=1,...,N

1.4 Search Options

1.4.1 Multiple Interactions at a Node

By default, ACME defines only one interaction at a node. If potential interactions with more than one face are detected, ACME will return only one interaction (the best one, according to the algorithm used for competition between two interactions) to the host code. However, to get better behavior at a true corner of a body, multiple interactions with the faces surrounding the corner should be considered. Therefore, if desired, ACME can define multiple interactions at a node. When this feature is activated, the host code must specify an angle (in degrees) called SHARP_NON_SHARP_ANGLE. If the angle between connected faces (computed as the angle between the normals to the faces, as shown in Figure 8) is greater than SHARP_NON_SHARP_ANGLE, then an interaction will be defined for each face, instead of competition between the two to define one interaction. If the multiple interactions feature is not active, interactions with only one of two disconnected faces will be returned (see Figure 9). Interactions with disconnected faces will be returned to the host code regardless of the angle.

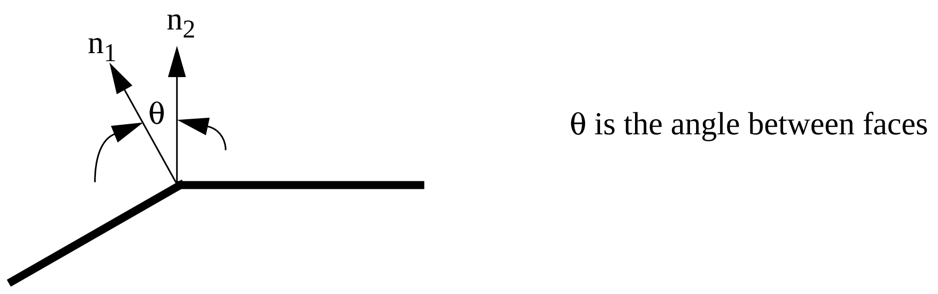


Figure 8 Definition of Angle Between Faces

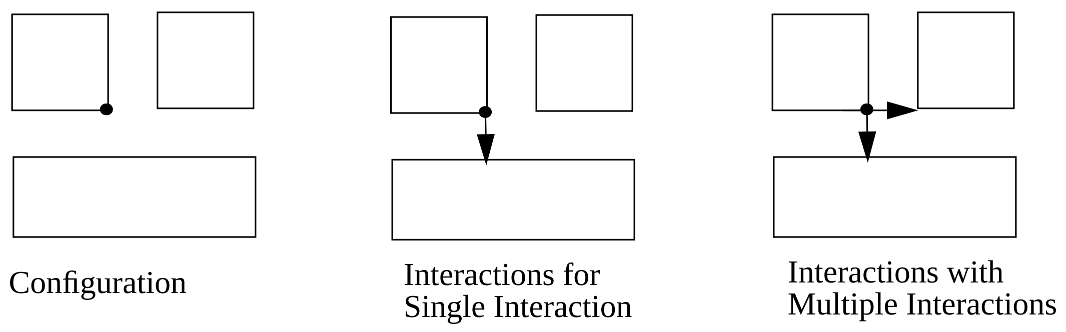

Configuration
Interactions for Single Interaction
Interactions with Multiple Interactions

Figure 9 Interactions for Single vs. Multiple Interaction Definition

1.4.2 Normal Smoothing

As previously noted, a NodeFace_Interaction consists of a contact point, a normal gap, a pushback direction, and a normal direction. The normal direction is an approximation of the normal to the surface at the contact point, which by default is simply the normal to the face. In some cases, however, it is necessary to have a continually varying normal without abrupt changes (e.g., when transitioning across an edge). The normal smoothing capability computes, if appropriate, a “smoothed” normal that varies continuously as a node transitions between faces. Smoothing occurs if the contact point is within a user-specified distance to the edge and if the included angle between the faces is less than the SHARP_NON_SHARP_ANGLE (see Figure 10). The contact point, normal gap, and pushback direction are not modified by normal smoothing.

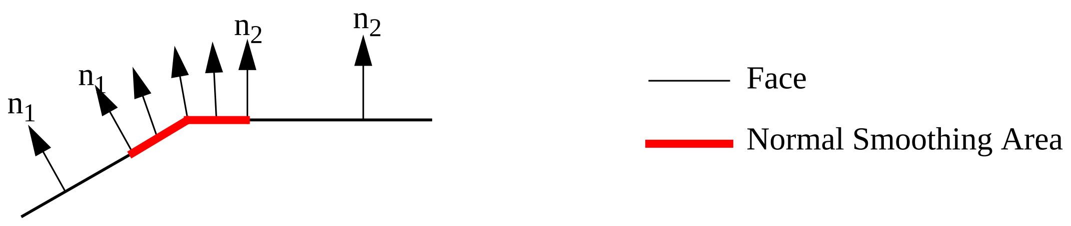
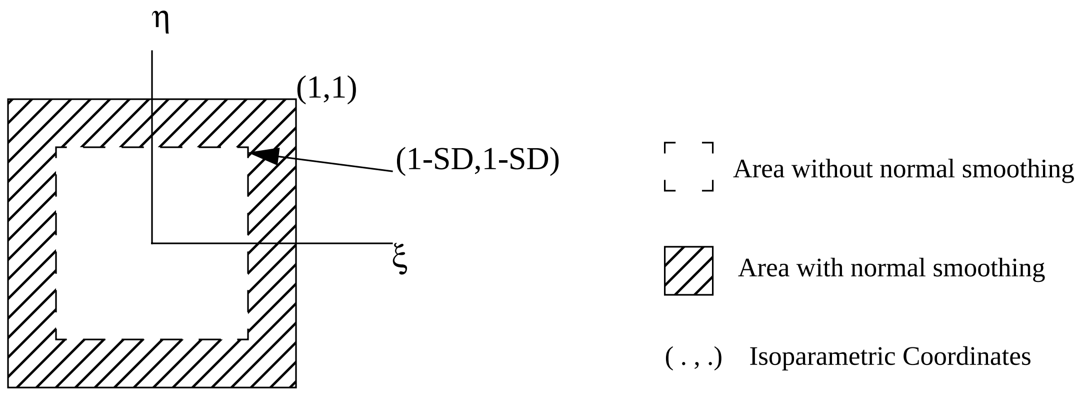


Figure 10 Normal Smoothing Across an Edge

When activating this feature, the host code must specify a SHARP_NON_SHARP_ANGLE (in degrees), a normal smoothing distance, and a RESOLUTION_METHOD for cases when a unique solution cannot be determined. If the angle between two faces is greater than the SHARP_NON_SHARP_ANGLE, then the edge is considered SHARP and no smoothing will be done to the normal. The angle specified for normal smoothing must match the angle specified for multiple interactions if that capability is active.

The normal smoothing distance (SD) specifies the region over which normal smoothing occurs (see Figure 11). This distance is in isoparametric coordinates, so its value ranges from 0 to 1 (in theory), but for practical purposes, 0.5 is an upper bound.



η
(1,1)
(1-SD,1-SD)
ξ
Area without normal smoothing
Area with normal smoothing
(. , .) Isoparametric Coordinates

Figure 11 Region of Normal Smoothing for a QuadFaceL4

For the case when a unique solution does not exist for a smoothed normal, two resolution methods are provided: USE_NODE_NORMAL and USE_EDGE_BASED_NORMAL. To illustrate the differences between these two approaches, consider Figure 12. This example consists of five faces in the configuration shown, and uses a SHARP_NON_SHARP_ANGLE of 30 degrees. The angles between faces 1 and 5 and between faces 3 and 4 are greater than the SHARP_NON_SHARP_ANGLE, so the smoothing algorithm should not smooth between these faces. Smoothing is done between faces 1 and 2 and between faces 2 and 3, because the corresponding angles are less than 30 degrees. For points approaching the shared intersection of faces 1, 2, and 3, however, the two options ACME provides for determining the smoothed normal deliver different results. The USE_NODE_NORMAL option defines the normal at the intersection point to be the node normal and thus provides a continuously smooth normal in the region near the point. The problem with this approach in this particular case is that the node normal also includes the effects of faces 4 and 5, and thus effectively provides smoothing over the boundary between faces 1 and 5. Alternatively, the USE_EDGE_BASED_NORMAL option only considers smoothing between a pair of faces. This approach ensures that no smoothing occurs between faces 1 and 5, but it unfortunately can provide a different normal if we approach the intersection point from face 1 than if we approach the point from face 3. Therefore, the smoothed normal at the intersection point can be discontinuous, which can cause numerical problems in some applications. This feature will be addressed further as host codes gain experience on what approaches provide the best behavior.

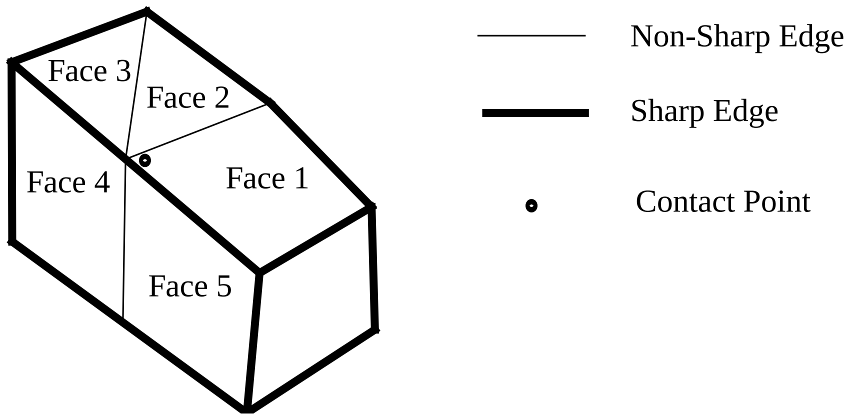


Figure 12 Illustration of Normal Smoothing Resolution

1.5 Gap Removal Enforcement

An optional gap removal enforcement is also included in ACME. Initial gaps often occur in meshes where curved geometries are discretized using varying mesh densities. The discretization error causes nodes from one (or more) surfaces to penetrate other surfaces. This initial gap can cause problems in explicit transient dynamic simulations (as well as other physics simulations) if the initial gap is large enough to cause interactions to be missed or if the initial gap is enforced on the first step, causing a large force. An effective method for avoiding these problems is to search for initial gaps and remove them in a strain-free manner (i.e., the initial topology is modified to remove the initial gaps). The enforcement object will compute the displacement correction needed to remove these initial gaps. Although it is not possible to have all nodes exactly on the faces of the other surface for curved geometries (it is an overconstrained problem), the gap removal enforcement seeks to satisfy the inequality that all gaps are non-negative with a minimum normal gap.

The gap removal enforcement should be used after performing a static 1-configuration search. The typical sequence for an explicit transient dynamic simulation would be:

1) Set the Search_Data array appropriate for an initial gap search.
2) Perform a static 1-configuration search.
3) Call ContactGapRemoval::Compute_Gap_Removal.
4) Apply the displacement correction from step 3 to the topology.
5) Initialization (compute volume, mass, etc. using the modified topology).

1.6 Explicit Transient Dynamic Enforcement

An optional explicit transient dynamic enforcement capability is included in ACME. The algorithm was written assuming that the host code is integrating the equations of motion using a central difference time integrator. The topology, interactions, and configurations are taken directly from a ContactSearch object (i.e., the enforcement is dependent on a

ContactSearch object). This capability takes as input the nodal masses from the host and returns the nodal forces that need to be applied.

The explicit transient dynamic enforcement can only be used in conjunction with the dynamic 2-configuration or dynamic augmented 2-configuration search methods. Following gap removal (if desired) and initialization, the continuation of the typical sequence for an explicit transient dynamic simulation would be:

6) Set the Search_Data array appropriate for the analysis.
7) Time Step using
   a) a dynamic or dynamic augmented 2-configuration search.
   b) a ContactTDEnforcement enforcement.

Two parameters, KINEMATIC_PARTITION and FRICTION_MODEL_ID, must be supplied by the host code for each possible entity pair. The KINEMATIC_PARTITION pertains to the fraction of total momentum each contacting surface will absorb. For example, if surface 1 contacts surface 2 and the kinematic partition for surface 1 is k, then the kinematic partition for surface 2 with respect to surface 1 is 1-k. Furthermore, if k is 1, then surface 1 acts as a “slave” to surface 2. The FRICTION_MODEL_ID refers to the particular friction model requested by the host code. There are currently three friction models available: frictionless, constant Coulomb friction, and tied. For NodeFace_Interactions and NodeSurface_Interactions, tied, frictionless, and frictional conditions can be enforced at a node. If these constraints are independent (e.g., three separate contact constraints at the corner of a block), the enforcement delivers the expected result. For conflicting constraints, a least-squares methodology is employed to resolve the forces required to effect the simultaneous interacting contact conditions.

1.7 Errors

ACME will trap internal errors whenever possible and return gracefully to the host code. ACME will *never* try to recover from an error; it will simply return control to the host code. The host code, therefore, has the final decision of how to proceed. At the moment an internal error is detected, ACME will immediately return to the host code without attempting to finish processing or attempting to ensure its internal data are consistent. As a result, it is essential that the host code check for errors. Interactions may not be reasonable if an internal error was encountered.

Errors are reported in two ways. First, all public access functions that could encounter an error return a ContactErrorCode (an enumeration in the ContactSearch header file). This error return code will be globally synchronized (i.e., all processors will return the same value).

The current enumeration for error codes is:

```
enum ContactErrorCode{
   NO_ERROR = 0,
   ID_NOT_FOUND,
   UNKNOWN_TYPE,
        INVALID_ID,
        INVALID_DATA,
        UNIMPLEMENTED_FUNCTION,
        ZOLTAN_ERROR,
        EXODUS_ERROR,
        INVALID_INTERACTION,
        INTERNAL_ERROR };
```

The return value is meant as an easy check for the host code to determine if an error occurred on any processor. It does not specify which processor encountered the error, nor does it return a real description of the error or the ID (if appropriate) to determine on what entity the error occurred (e.g., which unimplemented function was called or, possibly in the future, which face has a negative area). ACME does not normally write any data to the standard output or error files (stdout or stderr). Instead, ACME provides functions to extract detailed error information line by line, which the host code can then direct to its own output files as desired. Each line is limited to 80 characters.

1.8 Plotting

ACME can be built with a compile-time option to include an ExodusII plotting capability. The host code is responsible for creating the ExodusII file, including the name and location of the plot file. It is also responsible for closing the file after ACME writes its data. Because ACME writes double precision data, this file must be created with the ExodusII parameter ICOMPWS set to 8.

If the host code desires a plot file from ACME, it *must* create a new file for each time step. This capability is primarily intended as a debugging tool and is not envisioned for use in production calculations. Since the host code specifies the mesh topology and has access to the interactions, it has the ability to include the interaction data in its normal plotting functionality as it sees fit.

The mesh coordinates for each plot file are always taken as those in the current configuration. The displacements are the differences between the predicted and current coordinates if the predicted coordinates have been specified; otherwise the displacements are set to zero. Each Face_Block is treated as an element block (TRI3 for TRIFACEL3, TRI6 for TRIFACEQ6, and SHELL for QUADFACEL4 and QUADFACEQ8). Additional element blocks, one for each edge type, are created to represent the edges (BAR for LineEdgeL2 and BAR3 for LineEdgeQ3). An additional TRI3 element block is created to represent the FaceFace_Interactions. An additional BAR element block is created to represent the FaceCoverage_Interactions. Because ExodusII does not support node blocks, all the nodes are output without their associated Node_Block. The global output variables are listed in Table 5.

Table 5 Global Variables for ExodusII Output

Name	Description
num_nf_interactions	total number of NodeFace_Interactions
num_ns_interactions	total number of NodeSurface_Interactions
num_ff_interactions	total number of FaceFace_Interactions
num_fc_interactions	total number of FaceCoverage_Interactions
mult_interaction_status	flag indicating if multiple interactions is on/off
norm_smoothing_status	flag indicating if normal smoothing is on/off
smoothing_angle	SHARP_NON_SHARP_ANGLE for normal smoothing
smoothing_length	SD for normal smoothing
smoothing_resolution	RESOLUTION_METHOD for normal smoothing

The nodal output variables include both the nodal data (displacement and node normal) and the interactions (NodeFace_Interactions and NodeSurface_Interactions). The interactions are output for their associated node, rather than with the face. Currently, up to three interactions at a node can be output, with no meaning attached to their order. If a node has no interactions, all of the interaction data for that node will be zero. If a node has one interaction, the second and third sets of interaction data will all be zero, etc. Table 6 gives a description of all the nodal data written to the ExodusII file. (UNIX-style notation using square brackets to form regular expressions is used in this and subsequent tables. For example, displ[xyz] is shorthand for displx, disply, and displz.)

Table 6 Nodal Variables for ExodusII Output

Name	Description
displ[xyz]	X, Y & Z components of displacement
nnorm[xyz]	X, Y & Z components of the unit node normal
numcon	number of kinematic constraints at the node
convec[xyz]	X, Y & Z components of kinematic constraint vector (provided by host)
face_id[123]	The ID of the face involved in interaction 1, 2, or 3 (0 if no interaction)

Table 6 Nodal Variables for ExodusII Output

Name	Description
alg[123]	algorithm used to define interaction 1, 2, or 3 (1=closest point projection for 1-configuration search, 2=closest point projection for 2-configuration search, 3=moving_intersection)
node_ek[123]	The node entity key for interaction 1, 2, or 3 (0 if no interaction)
gapcur[123]	The Gap arising from the current time step, not including any residual Gap (0 if no interaction)
gapold[123]	The residual Gap from the previous time step for interaction 1, 2, or 3 (0 if no interaction)
pbdir[123][xyz]	X, Y, & Z components of the pushback direction for interaction 1, 2, or 3 (0 if no interaction)
ivec[123][xyz]	X, Y, & Z components of a vector that, when drawn from the node, gives the location of the interaction point for interaction 1, 2, or 3 (0 if no interaction)
norm[123][xyz]	X, Y, & Z components of the normal to the surface at the interaction point for interaction 1, 2, or 3
pfnorm[123][xyz]	X, Y, & Z components of the physical face normal for the node for interaction 1, 2, or 3. (The physical face concept is used to obtain face to face contact without the full expense. A node on a flat surface will only have one physical face, while a node at the corner of a cube would have three physical faces (one for each of the three intersecting planes)
iveca[xyz]	X, Y, & Z components of a vector that, when drawn from the node, gives the location of the interaction point with an Analytic_Surface (0 if no interaction). This item is included only for problems with Analytic_Surfaces.
Global_ID	The global ID for the node supplied by the host code in the constructor
Primary_Owner	The processor that owns the node in the primary decomposition
Primary_Local_ID	The local ID for the node on the owning processor
Secondary_Owner	The processor that owns the node in the secondary decomposition
EnfVar[xyz]	X, Y, & Z components of a vector that is the force for ContactTDEnforcement and the displacement correction for ContactGapRemoval.

The “element” data actually consist of the face and edge data (since both are output as element blocks). The FaceFace_Interaction and FaceCoverage_Interaction data are also stored as element data. Table 7 gives the names and descriptions of the element data written to the ExodusII file.

Table 7 Element Variables for ExodusII Output

Name	Entity	Description
fnorm[xyz]	Faces	Unit face normal at centroid
curvature	Edges	0 = Unknown 1 = Convex 2 = Concave 3 = Concave with smoothing 4 = Convex with smoothing
angle_bf	Edges	The angle between the two faces connected to this edge. The value is zero if the edge is only connected to one face.
FFI[0-N]_FACE_ID	Faces	the ID of the master face involved in interaction 0, 1, ..., N=num_ffi_interactions-1
FFI[0-N]_NVERTS	Faces	the number of vertexes/edges in the polygon for interaction 0, 1, ..., N=num_ffi_interactions-1
FFI[0-N]_SX[0-M]	Faces	the 1st local coordinate on the slave face for interaction 0, 1, ..., N=num_ffi_interactions-1 and vertex 0, 1, ..., M=nverts-1
FFI[0-N]_SY[0-M]	Faces	the 2nd local coordinate on the slave face for interaction 0, 1, ..., N=num_ffi_interactions-1 and vertex 0, 1, ..., M=nverts-1
FFI[0-N]_MX[0-M]	Faces	the 1st local coordinate on the master face for interaction 0, 1, ..., N=num_ffi_interactions-1 and vertex 0, 1, ..., M=nverts-1
FFI[0-N]_MY[0-M]	Faces	the 2nd local coordinate on the master face for interaction 0, 1, ..., N=num_ffi_interactions-1 and vertex 0, 1, ..., M=nverts-1
FFI[0-N]_EDGE[0-M]	Faces	the flag indicating coincidence with an edge on the slave face for interaction 0, 1, ..., N=num_ffi_interactions-1 and vertex 0, 1, ..., M=nverts-1

Table 7 Element Variables for ExodusII Output

Name	Entity	Description
FFI[0-N]_FLAG[0-M]	Faces	the flag indicating coincidence with an edge on the master face for interaction 0, 1, ..., N=num_ffi_interactions-1 and vertex 0, 1, ..., M=nverts-1
FCI[0-N]_NVERTS	Faces	the number of vertexes/edges in the polygon for interaction 0, 1, ..., N=num_fci_interactions-1
FCI[0-N]_X[0-M]	Faces	the 1st local coordinate on the face for interaction 0, 1, ..., N=num_fci_interactions-1 and vertex 0, 1, ..., M=nverts-1
FCI[0-N]_Y[0-M]	Faces	the 2nd local coordinate on the face for interaction 0, 1, ..., N=num_fci_interactions-1 and vertex 0, 1, ..., M=nverts-1
PrimaryOwner	Both	The processor that owns the entity in the primary decomposition
PrimaryLocalID	Both	The local ID for the entity on the owning processor
SecondaryOwner	Both	The processor that owns the entity in the secondary decomposition

1.9 Restart Capabilities

ACME currently provides two options for restart. The first restart option is a binary data stream, where all of the data are packed into one array to be written to a restart file. This binary data stream can then be used with a special constructor to restore the objects to their original state. The second restart option allows a host code to extract node, edge and face restart variables one at a time to be output to a restart file. The variable-based restart requires the host code to call the basic constructor for the objects and then “implant” the restart variables into the object, which restores the objects to their states before the restart. Both restart methods currently require that neither the mesh topology nor the decomposition change. Eventually, the ability to restart with a different number of processors will be supported with the variable-based restart capability; it will not be supported with the binary stream restart function.

2. Utility Functions

ACME provides various utility functions that are either independent of the search and enforcement objects or are identical for those objects. These include functions to obtain information about the current version of ACME, to extract information about errors encountered within the ACME algorithms, to extract data needed to restart ACME processing, and to create ExodusII plot files.

In each section delineating the ACME API functions (Sections 2, 3, 4, and 5), the different forms for the C++, C, and Fortran syntax are presented together for each function call. The C++ API uses the full object-oriented capabilities of the language. On the other hand, the C and Fortran APIs, which in actuality have been combined into a single interface, are a collection of functions that have a pure C interface and can be called from either C or Fortran rountines. The FORTRAN macro that surrounds all calls in the C syntax converts the function by appending an underscore to the end of the function name, if appropriate. Because of this, all data in the C API must be passed by address, not by value. For Fortran, there exists no capability to pass data by value, so simply specifying the name of the variable or array will allow it to be passed appropriately.

The Search_Interface.h header file, located in the ACME search directory, includes the prototypes for the C and Fortran functions described in this chapter, and the ContactSearch.h file includes the C++ prototypes. Enumerations for symbolic types used in the C++ API are also found in ContactSearch.h; these indicate the acceptable integral values that may be used in the C and Fortran APIs.

2.1 Version Information

Functions are provided to obtain the ACME version number and its release date and to check the compile-time compatibility of the ACME library and the host code with respect to the MPI library.

2.1.1 Getting the Version ID

The following function returns the version of ACME, which is a character string of the form x.yz, where x is an integer representing the major version, y is an integer representing the minor version, and z is a letter representing the bug fix level. The initial release of this version of ACME will be 1.0a, the first bux fix release will be 1.0b, and so on. The prototype for this function is:

```
C++      const char* ACME_Version();

C        void FORTRAN(acme_version)( char* vers );

Fortran  acme_version( vers )
```

where

vers is an array of characters of length 80 (in C, 81 including the terminal ‘\n’).

2.1.2 Getting the Version Date

The following function returns the release date for ACME, which is a character string of the form ‘September 28, 2001’ (the current release date). The prototype for this function is:

```
C++      const char* ACME_VersionDate();

C        void FORTRAN(acme_versiondate)( char* vers_date );

Fortran  acme_versiondate( vers_date )
```

where

vers_date is an array of characters of length 80 (in C, 81 including the terminal ‘\n’).

2.1.3 Checking Compatibility with MPI

The following function returns an error if the compilations of the host code and the ACME library are incompatible with respect to the MPI library. The host code should call this function with the host_compile argument set to MPI_COMPILE, which is defined in the ContactSearch header file to be 0 if CONTACT_NO_MPI is defined at compile time, and defined as 1 otherwise. This function will check for compatibility with the value of MPI_COMPILE defined during compilation of the ACME library. The prototype for this function is:

```
C++      int ACME_MPI_Compatibility(int host_compile);

C        void FORTRAN(acme_mpi_compatibility)
                     ( int* host_compile, int* error );

Fortran  acme_mpi_compatibility( host_compile, error )
```

where

host_compile is the value of MPI_COMPILE used during compilation of the host code.
error is the return error code for the C and Fortran APIs.

2.2 Errors

As discussed in Section 1.7, ACME attempts to trap internal errors whenever possible. There are C-style character strings that can be extracted that give a detailed description of what error(s) occurred during ACME processing for the search and enforcement objects. These strings are specific to the current processor. Therefore, each processor may have a different number of error messages. The error return code is synchronized in parallel so all processors return the same error code even if a processor did not encounter an error.

2.2.1 Getting the Number of Errors

The following functions, which are public member functions in the C++ API, determine how many error messages the current processor has written. The prototypes for these functions are:

```
C++      int ContactSearch::Number_of_Errors();
         int ContactTDEnforcement::Number_of_Errors();
         int ContactGapRemoval::Number_of_Errors();

C        FORTRAN(number_of_search_errors)( int* num_errors );
         FORTRAN(number_of_td_errors)( int* num_errors );
         FORTRAN(number_of_gap_errors)( int* num_errors );

Fortran  number_of_search_errors( num_errors )
         number_of_td_errors( num_errors )
         number_of_gap_errors( num_errors )
```

where

num_errors is the number of error messages that should be extracted by the host code.

2.2.2 Extracting Error Messages

The following functions, which are public member functions in the C++ API, can be used to extract the character strings for each error message on a processor (the number of which can be determined by the functions described in the previous section):

```
C++      const char* ContactSearch::Error_Message( int i );
         const char* ContactTDEnforcement::Error_Message( int i );
         const char* ContactGapRemoval::Error_Message( int i );

C        FORTRAN(get_search_error_message)(
                   int* i,
                   char* message );
         FORTRAN(get_td_error_message)(
                   int* i,
                   char* message );
         FORTRAN(get_gap_error_message)(
                   int* i,
                   char* message );

Fortran  get_search_error_message( i, message )
         get_td_error_message( i, message )
         get_gap_error_message( i, message )
```

where

i is the Fortran index of the error message (i.e., 1 to Number_of_Errors(), or num_errors for C and Fortran).
message is an array of characters of length 80 (in C, 81 including the terminal ‘\n’).

2.3 Binary Stream Restart Functions

ACME provides functionality to allow restart using a single binary stream of data for each ACME search or enforcement object. The host code is responsible for allocating the array to hold the data, calling the functions, and writing the data to a restart file. Upon restart, the host code should supply the binary data stream to the special constructors described in this section, which will restore the objects to their state before restart.

2.3.1 Getting the Binary Restart Size

The following functions allow the host code to determine how much memory to allocate to store restart information for the search and enforcement objects. The return value is the number of double locations that are needed.

```
C++      int ContactSearch::Restart_Size();
         int ContactTDEnforcement::Restart_Size();
         int ContactGapRemoval::Restart_Size();

C        FORTRAN(search_restart_size)( int* size );
         FORTRAN(td_enf_restart_size)( int* size );
         FORTRAN(gap_removal_restart_size)( int* size );

Fortran  search_restart_size( size );
         td_enf_restart_size( size );
         gap_removal_restart_size( size );
```

where

size is the number of double locations that are needed for the restart data.

2.3.2 Extracting the Binary Restart Data

The following functions allow the host code to extract all the information needed to initialize an ACME object to its current state.

```
C++      ContactErrorCode
         ContactSearch::Extract_Restart_Data(
                   double* restart_data);
         ContactErrorCode
         ContactTDEnforcement::Extract_Restart_Data(
                   double* restart_data);
         ContactErrorCode
         ContactGapRemoval::Extract_Restart_Data(
                   double* restart_data);

C        FORTRAN(search_extract_restart)(
                   double* restart_data,
                   int* error);
         FORTRAN(td_enf_extract_restart)(
                   double* restart_data,
                   int* error);
```

```
          FORTRAN(gap_removal_extract_restart)(
                    double* restart_data,
                    int* error);

Fortran   search_extract_restart( restart_data, error)
          td_enf_extract_restart( restart_data, error)
          gap_removal_extract_restart( restart_data, error)
```

where

restart_data is an array of type double. The length of this array is obtained from the function Restart_Size() (see the previous section).
error is the return error code for the C and Fortran APIs.

2.3.3 Constructing Objects Upon Restart

As noted above, a second constructor is available to allow for restarts from the binary data stream provided by the Extract_Restart_Data functions described in Section 2.3.2:

```
C++       ContactSearch::ContactSearch(
                    const double* restart_data,
                    const MPI_Comm& mpi_communicator,
                    ContactErrorCode& error );
          ContactTDEnforcement::ContactTDEnforcement(
                    ContactSearch* search,
                    double* restart_data,
                    int* error );
          ContactGapRemoval::ContactGapRemoval(
                    ContactSearch* search,
                    double* restart_data,
                    int* error );

C         FORTRAN(build_search_restart)(
                    double* restart_data,
                    int* mpi_communicator,
                    int* error );

          FORTRAN(build_td_enf_restart)(
                    double* restart_data,
                    int* error );
          FORTRAN(build_gap_removal_restart)(
                    double* restart_data,
                    int* error );

Fortran   build_search_restart(
                    restart_data,
                    mpi_communicator,
                    error )
          build_td_enf_restart(
                    restart_data,
                    error )
```

```
             build_gap_removal_restart(
                       restart_data,
                       error )
```

where

restart_data is an array of type double. The length of this array is obtained from the function Restart_Size() (see the previous section).
mpi_communicator is an MPI communicator if ACME was built for a parallel and is simply a dummy int otherwise.
search is the associated ContactSearch object for this enforcement object. This is hidden in the C and Fortran APIs because only one search object is allowed.
error is the error return code that will reflect any errors that were detected.

2.4 Variable-Based Restart Functions

The variable-based restart functions allow a host code to extract all the restart variables from the ACME objects variable by variable. This set of functions will eventually allow restarts on different numbers of processors, although that capability is not supported in this release. There are no separate constructors for this type of restart. Instead, the traditional constructor is used and then the variable-based data are “implanted.”

2.4.1 Obtaining the Number of Nodal Restart Variables

These functions supply the number of nodal variables from each search and enforcement object that need to be written to (or read from) a restart file.

```
C++      int ContactSearch::Number_Nodal_Restart_Variables();
         int
         ContactTDEnforcement::Number_Nodal_Restart_Variables();
         int ContactGapRemoval::Number_Nodal_Restart_Variables();

C        FORTRAN( search_num_nrsvars )( int* num_nvars );
         FORTRAN( td_enf_num_nrsvars )( int* num_nvars );
         FORTRAN( gap_removal_num_nrsvars) ( int* num_nvars );

Fortran  search_num_nrsvars( num_nvars )
         td_enf_num_nrsvars( num_nvars )
         gap_removal_num_nrsvars( num_nvars )
```

where

num_nvars is the number of nodal restart variables

2.4.2 Obtaining the Number of Edge Restart Variables

These functions supply the number of edge variables from each search and enforcement object that need to be written to (or read from) a restart file. Currently, there are no edge-based restart variables, so the ambiguity of how to handle the issue that edges are internally generated, not supplied by the host code, is deferred until edge-based restart variables are required. These functions are included here to complete the API.

```
C++      int ContactSearch::Number_Edge_Restart_Variables();
         int ContactTDEnforcement::Number_Edge_Restart_Variables();
         int ContactGapRemoval::Number_Edge_Restart_Variables();

C        FORTRAN( search_num_ersvars )( int* num_evars );
         FORTRAN( td_enf_num_ersvars )( int* num_evars );
         FORTRAN( gap_removal_num_ersvars) ( int* num_evars );

Fortran  search_num_ersvars( num_evars )
         td_enf_num_ersvars( num_evars )
         gap_removal_num_ersvars( num_evars )
```

where

num_evars is the number of edge restart variables

2.4.3 Obtaining the Number of Face Restart Variables

These functions supply the number of face variables from each search and enforcement object that need to be written to (or read from) a restart file.

```
C++      int ContactSearch::Number_Face_Restart_Variables();
         int ContactTDEnforcement::Number_Face_Restart_Variables();
         int ContactGapRemoval::Number_Face_Restart_Variables();

C        FORTRAN( search_num_frsvars )( int* num_fvars );
         FORTRAN( td_enf_num_frsvars )( int* num_fvars );
         FORTRAN( gap_num_frsvars) ( int* num_fvars );

Fortran  search_num_frsvars( num_fvars )
         td_enf_num_frsvars( num_fvars )
         gap_num_frsvars( num_fvars )
```

where

num_fvars is the number of face restart variables

2.4.4 Extracting the Nodal Restart Variables

These functions extract the nodal variables, one by one, that are required for restart.

```
C++      ContactErrorCode
         ContactSearch::Extract_Nodal_Restart_Variable(
                   int variable_number,
                   double* variable_data );
         ContactErrorCode
         ContactTDEnforcement::Extract_Nodal_Restart_Variable(
                   int variable_number,
                   double* variable_data );
         ContactErrorCode
         ContactGapRemoval::Extract_Nodal_Restart_Variable(
                   int variable_number,
                   double* variable_data );

C        FORTRAN(search_extract_nrsvars)(
                   int variable_number,
                   double* variable_data,
                   int* error );
         FORTRAN(td_extract_nrsvars)(
                   int variable_number,
                   double* variable_data,
                   int* error );
         FORTRAN(gap_extract_nrsvars)(
                   int variable_number,
                   double* variable_data,
                   int* error );


Fortran  search_extract_nrsvars(
                   variable_number,
                   variable_data,
                   error )
         td_extract_nrsvars(
                   variable_number,
                   variable_data,
                   error )
         gap_extract_nrsvars(
                   variable_number,
                   variable_data,
                   error )
```

where

variable_number is the variable number (using Fortran indexing; i.e, from 1 to N).
variable_data is an array of type double. The length of the array is given by the number of nodes in the surface topology for this processor (as supplied in the constructor).
error is the return error code for the C and Fortran APIs.

2.4.5 Implanting the Nodal Restart Variables

These functions implant the nodal variables, one by one, that are required for restart.

```
C++      ContactErrorCode
         ContactSearch::Implant_Nodal_Restart_Variable(
                   int variable_number,
                   double* variable_data );
         ContactErrorCode
         ContactTDEnforcement::Implant_Nodal_Restart_Variable(
                   int variable_number,
                   double* variable_data );
         ContactErrorCode
         ContactGapRemoval::Implant_Nodal_Restart_Variable(
                   int variable_number,
                   double* variable_data );

C        FORTRAN(search_impant_nrsvars)(
                   int variable_number,
                   double* variable_data,
                   int* error );
         FORTRAN(td_implant_nrsvars)(
                   int variable_number,
                   double* variable_data,
                   int* error );
         FORTRAN(gap_implant_nrsvars)(
                   int variable_number,
                   double* variable_data,
                   int* error );

Fortran  search_implant_nrsvars(
                   variable_number,
                   variable_data,
                   error )
         td_implant_nrsvars(
                   variable_number,
                   variable_data,
                   error )
         gap_implant_nrsvars(
                   variable_number,
                   variable_data,
                   error )
```

where

variable_number is the variable number (using Fortran indexing; i.e, from 1 to N).
variable_data is an array of type double. The length of the array is given by the number of nodes in the surface topology for this processor (as supplied in the constructor).

2.4.6 Extracting the Edge Restart Variables

These functions extract the edge variables, one by one, that are required for restart. As previously mentioned, there are currently no edge-based restart variables, so these functions will not be used in this version of ACME.

```
C++      ContactErrorCode
         ContactSearch::Extract_Edge_Restart_Variable(
                    int variable_number,
                    double* variable_data );
         ContactErrorCode
         ContactTDEnforcement::Extract_Edge_Restart_Variable(
                    int variable_number,
                    double* variable_data );
         ContactErrorCode
         ContactGapRemoval::Extract_Edge_Restart_Variable(
                    int variable_number,
                    double* variable_data );

C        FORTRAN(search_extract_ersvars)(
                    int variable_number,
                    double* variable_data,
                    int* error );
         FORTRAN(td_extract_ersvars)(
                    int variable_number,
                    double* variable_data,
                    int* error );
         FORTRAN(gap_extract_ersvars)(
                    int variable_number,
                    double* variable_data,
                    int* error );

Fortran  search_extract_ersvars(
                    variable_number,
                    variable_data,
                    error )
         td_extract_ersvars(
                    variable_number,
                    variable_data,
                    error )
         gap_extract_ersvars(
                    variable_number,
                    variable_data,
                    error )
```

where

variable_number is the variable number (using Fortran indexing; i.e, from 1 to N).
variable_data is an array of type double. The length of the array is given by the number of edges in the surface topology for this processor.

2.4.7 Implanting the Edge Restart Variables

These functions implant the edge variables, one by one, that are required for restart. As previously mentioned, there are currently no edge-based restart variables so these functions will not be used in this version of ACME.

```
C++      ContactErrorCode
         ContactSearch::Implant_Edge_Restart_Variable(
                   int variable_number,
                   double* variable_data );
         ContactErrorCode
         ContactTDEnforcement::Implant_Edge_Restart_Variable(
                   int variable_number,
                   double* variable_data );
         ContactErrorCode
         ContactGapRemoval::Implant_Edge_Restart_Variable(
                   int variable_number,
                   double* variable_data );

C        FORTRAN(search_impant_ersvars)(
                   int variable_number,
                   double* variable_data,
                   int* error );
         FORTRAN(td_implant_ersvars)(
                   int variable_number,
                   double* variable_data,
                   int* error );
         FORTRAN(gap_implant_ersvars)(
                   int variable_number,
                   double* variable_data,
                   int* error );

Fortran  search_implant_ersvars(
                   variable_number,
                   variable_data,
                   error )
         td_implant_ersvars(
                   variable_number,
                   variable_data,
                   error )
         gap_implant_ersvars(
                   variable_number,
                   variable_data,
                   error )
```

where

variable_number is the variable number (using Fortran indexing; i.e, from 1 to N).
variable_data is an array of type double. The length of the array is given by the number of edges in the surface topology for this processor.

2.4.8 Extracting the Face Restart Variables

These functions extract the face variables, one by one, that are required for restart.

```
C++      ContactErrorCode
         ContactSearch::Extract_Face_Restart_Variable(
                   int variable_number,
                   double* variable_data );
         ContactErrorCode
         ContactTDEnforcement::Extract_Face_Restart_Variable(
                   int variable_number,
                   double* variable_data );
         ContactErrorCode
         ContactGapRemoval::Extract_Face_Restart_Variable(
                   int variable_number,
                   double* variable_data );

C        FORTRAN(search_extract_frsvars)(
                   int variable_number,
                   double* variable_data,
                   int* error );
         FORTRAN(td_extract_frsvars)(
                   int variable_number,
                   double* variable_data,
                   int* error );
         FORTRAN(gap_extract_frsvars)(
                   int variable_number,
                   double* variable_data,
                   int* error );

Fortran  search_extract_frsvars(
                   variable_number,
                   variable_data,
                   error )
         td_extract_frsvars(
                   variable_number,
                   variable_data,
                   error )
         gap_extract_nrsvars(
                   variable_number,
                   variable_data,
                   error )
```

where

variable_number is the variable number (using Fortran indexing; i.e, from 1 to N).
variable_data is an array of type double. The length of the array is given by the number of faces in the surface topology for this processor (as supplied in the constructor).

2.4.9 Implanting the Face Restart Variables

These functions implant the face variables, one by one, that are required for restart.

```
C++      ContactErrorCode
         ContactSearch::Implant_Face_Restart_Variable(
                    int variable_number,
                    double* variable_data );
         ContactErrorCode
         ContactTDEnforcement::Implant_Face_Restart_Variable(
                    int variable_number,
                    double* variable_data );
         ContactErrorCode
         ContactGapRemoval::Implant_Face_Restart_Variable(
                    int variable_number,
                    double* variable_data );

C        FORTRAN(search_impant_frsvars)(
                    int variable_number,
                    double* variable_data,
                    int* error );
         FORTRAN(td_implant_frsvars)(
                    int variable_number,
                    double* variable_data,
                    int* error );
         FORTRAN(gap_implant_frsvars)(
                    int variable_number,
                    double* variable_data,
                    int* error );

Fortran  search_implant_frsvars(
                    variable_number,
                    variable_data,
                    error )
         td_implant_frsvars(
                    variable_number,
                    variable_data,
                    error )
         gap_implant_frsvars(
                    variable_number,
                    variable_data,
                    error )
```

where

variable_number is the variable number (using Fortran indexing; i.e, from 1 to N).
variable_data is an array of type double. The length of the array is given by the number of faces in the surface topology for this processor (as supplied in the constructor).

2.4.10 Completing a Binary Stream Restart

These functions *must* be called after constructing an ACME object and implanting the restart variables with the functions described previously. These functions restore each ACME object to its state prior to restart. After these functions have been called, normal calculations can resume.

```
C++      ContactErrorCode ContactSearch::Complete_Restart();
         ContactErrorCode ContactTDEnforcement::Complete_Restart();
         ContactErrorCode ContactGapRemoval::Complete_Restart();

C        FORTRAN(search_complete_restart)( int* error );
         FORTRAN(td_enf_complete_restart)( int* error );
         FORTRAN(gap_complete_restart)( int* error );

Fortran  search_complete_restart( error )
         td_enf_complete_restart( error )
         gap_complete_restart( error )
```

where

error is the return error code for the C and Fortran APIs.

2.5 Creating an Exodus Plot File of the Search & Enforcement Data

ACME has the ability to write an ExodusII file that contains the full search topology and all of the interaction data, including enforcement results. This function can be used only if ACME was built with ExodusII support (a compile time option). See Section 1.8 for a detailed description of the data written to the ExodusII file. The host code is required to actually open and close the ExodusII file, so it must choose the name and location for the file. This file must be opened with ICOMPWS=8. The ExodusII ID is then passed to ACME, which writes the topology and the results data. Only one plot step can be written to each file. The number of variables in the database depends on the number of interaction types currently active in the search object (which can change each time step).

The prototype for this capability is:

```
C++      ContactErrorCode ContactSearch::Exodus_Output(
                    int exodus_id,
                    double time );

C        FORTRAN(exodus_output)(
                    int* exodus_id,
                    double* time,
                    int* error );

FORTRAN  exodus_output(
                    exodus_id,
                    time,
                    error )
```

where

exodus_id is the integer database ID returned by the ExodusII library from an ex_create call.
time is the time value for the “results” to be written to the ExodusII file.
error is the return error code for the C and Fortran APIs.

3. Search Functions

This section describes functions that construct and operate on ContactSearch "objects." For the C++ API, these are true objects permitted by the object-oriented capabilities of the language. There are no static variables, so an arbitrary number of objects may be simultaneously active. In the C and Fortran APIs, these functions create and operate on a ContactSearch "object," only one of which is currently allowed. Functions are provided to allow destruction of the ContactSearch object and creation of a new object at any point. Multiple objects can be supported in the future if the need ever arises.

There are two constructors for the ContactSearch object. The first, described in this section, is intended for general use, while the second, described in Section 2, is used to construct a search object using data read in from a previously generated restart file. The ContactSearch object is neither copy-able nor assignable.

In each section delineating the ACME API functions (Sections 2, 3, 4, and 5), the different forms for the C++, C, and Fortran syntax are presented together for each function call. The C++ API uses the full object-oriented capabilities of the language. On the other hand, the C and Fortran APIs, which in actuality have been combined into a single interface, are a collection of functions that have a pure C interface and can be called from either C or Fortran rountines. The FORTRAN macro that surrounds all calls in the C syntax converts the function by appending an underscore to the end of the function name, if appropriate. Because of this, all data in the C API must be passed by address, not by value. For Fortran, there exists no capability to pass data by value, so simply specifying the name of the variable or array will allow it to be passed appropriately.

The Search_Interface.h header file, located in the ACME search directory, includes the prototypes for the C and Fortran functions described in this chapter, and the ContactSearch.h file includes the C++ prototypes. Enumerations for symbolic types used in the C++ API are also found in ContactSearch.h; these indicate the acceptable integral values that may be used in the C and Fortran APIs.

3.1 Creating a ContactSearch Object

There is one general constructor for the ContactSearch object. A second constructor for restart is described in Section 2.3.2. The prototype for the general constructor is:

```
C++   ContactSearch::ContactSearch(
                   int dimensionality,
                   int number_of_states,
                   int number_of_entity_keys,
                   int number_of_node_blocks,
                   const ContactSearch::ContactNode_Type*
                      node_block_types,
                   const int* number_of_nodes_in_blocks,
                   const int* node_global_ids,
                   int number_of_face_blocks,
                   const ContactSearch::ContactFace_Type*
```

```
                         face_block_types,
                      const int* number_of_faces_in_blocks,
                      const int* connectivity,
                      int number_of_nodal_comm_partners,
                      const int* nodal_comm_proc_ids,
                      const int* number_of_nodes_to_partner,
                      const int* communication_nodes,
                      const MPI_Comm& mpi_communicator,
                      ContactErrorCode& error );
```

C
```
FORTRAN(build_search)(
          int* dimensionality,
          int* number_of_states,
          int* number_of_entity_keys,
          int* number_of_node_blocks,
          int* node_block_types,
          int* number_of_nodes_in_blocks,
          int* node_global_ids,
          int* number_of_face_blocks,
          int* face_block_types,
          int* number_of_faces_in_blocks,
          int* connectivity,
          int* number_of_nodal_comm_partners,
          int* nodal_comm_proc_ids,
          int* number_of_nodes_to_partner,
          int* communication_nodes,
          int* mpi_communicator,
          int* error );
```

Fortran
```
build_search(
          dimensionality,
          number_of_states,
          number_of_entity_keys,
          number_of_node_blocks,
          node_block_types,
          number_of_nodes_in_blocks,
          node_global_ids,
          number_of_face_blocks,
          face_block_types,
          number_of_faces_in_blocks,
          connectivity,
          number_of_nodal_comm_partners,
          nodal_comm_proc_ids,
          number_of_nodes_to_partner,
          communication_nodes,
          mpi_communicator,
          error );
```

where:

dimensionality is the number of spatial coordinates in the topology. Note: We are only supporting three dimensions in this release. Two-dimensional support will be added in the future.

number_of_states is the number of states the host code requests to be stored. A value of 1 implies that the ContactSearch object can not back up to an older state. A value of 2 will imply the ContactSearch object can back up to one old state, etc. For this release, this value *must* be 1.

number_of_entity_keys is the number of entity keys that will be used. This is currently the sum of the number of Face_Blocks and the number of Analytic_Surfaces.

number_of_node_blocks is the number of Node_Blocks in the topology. The first Node_Block contains the nodes connected to the faces specified in the Face_Blocks; additional Node_Blocks may contain other nodes that the host code needs to search against the faces.

node_block_types is an array (of length number_of_node_blocks) describing the type of nodes in each Node_Block. The current enumeration for this type in the C++ API is:

```
enum ContactSearch::ContactNode_Type{ NODE=1 };
```

number_of_nodes_in_blocks is an array (of length number_of_node_blocks) that gives the number of nodes in each Node_Block.

node_global_ids is an array containing the host code ID for each node. The IDs for the first Node_Block are listed first in the array, followed by the IDs for each of the other Node_Blocks in order (if applicable).

number_of_face_blocks is the number of Face_Blocks in the topology.

face_block_types is an array (of length number_of_face_blocks) describing the type of faces in each Face_Block. The current enumeration for this type in the C++ API is:

```
enum ContactSearch::ContactFace_Type{QUADFACEL4=1,
             QUADFACEQ8=2, TRIFACEL3=3, TRIFACEQ6=4};
```

number_of_faces_in_blocks is an array (of length number_of_face_blocks) that gives the number of faces in each Face_Block.

connectivity is a one-dimensional array that gives the connectivity (using Fortran indexing in the first Node_Block) for each face. The connectivity of each face is contiguous in memory and follows the ExodusII conventions for node order. The arrangement of this array may change when multiple Node_Blocks containing nodes related to faces are supported.

number_of_nodal_comm_partners is the number of processors that share nodes with the topology supplied to ACME on the current processor.

nodal_comm_proc_ids is an array (of length number_of_nodal_comm_partners) that lists the processor IDs that share nodes with the topology supplied to ACME on the current processor.

number_of_nodes_to_partner is an array (of length number_of_nodal_comm_partners) that gives the number of nodes shared with each processor in nodal_comm_proc_ids.

communication_nodes is an array that lists the nodes in the topology supplied to ACME that are shared, grouped by processor in the order specified in nodal_comm_proc_ids.

mpi_communicator is an MPI_Communicator.

error is the error code. This reflects any errors detected during execution of this method. A non-zero result indicates an error has occurred.

If the ACME library is built in pure serial mode (i.e., CONTACT_NO_MPI is defined during compilation), then number_of_nodal_comm_partners should be set to 0 and dummy pointers can be supplied for nodal_comm_proc_ids, number_of_nodes_to_partner, and communication_nodes. Furthermore, any integer value can be used for mpi_communicator, which is ignored.

3.2 Search_Data Array

As described in Section 1.1.4, Search_Data is a three-dimensional Fortran-ordered array for specifying entity pair data. The first index in the array refers to the data parameter, and the next two indexes refer to the keys for the two entities for which that parameter is applicable.

3.2.1 Checking the Search_Data Array Size

The following interface allows for checking the size of Search_Data expected by ACME. This is intended to be a check by the host code to ensure that ACME and the host code have a consistent view of the Search_Data array.

```
C++      ContactErrorCode ContactSearch::Check_Search_Data_Size(
                   int size_data_per_pair,
                   int number_of_entity_keys );

C        FORTRAN(check_search_data_size)(
                   int* size_data_per_pair,
                   int* number_of_entity_keys,
                   int* error );

Fortran  check_search_data_size(
                   size_data_per_pair,
                   number_of_entity_keys,
                   error )
```

where

size_data_per_pair is the number of data parameters for each entity pair (currently 3).
number_of_entity_keys is the number of entity keys.
error is the return error code for the C and Fortran APIs.

3.2.2 Setting Values in the Search_Data Array

The following interface allows the host code to specify the Search_Data array (see Section 1.1.4), which must be set prior to calling any of the search algorithms. This function can be called at any time to change values in the Search_Data array (e.g., to change tolerances).

```
C++      void ContactSearch::Set_Search_Data(
                   const double* search_data);

C        FORTRAN(set_search_data)(
                   double* search_data );

Fortran  set_search_data(
                   search_data )
```
where

search_data is an array of double precision values for the Search_Data (see Section 1.1.4).

3.3 Analytic_Surfaces

ACME supports the determination of interactions of nodes with Analytic_Surfaces. Currently, the only supported Analytic_Surfaces are a plane, a sphere, and two types of cylinders (one for a container and one for a post). The types of Analytic_Surfaces supported will be expanded in the future. The ACME ID for an Analytic_Surface is the number of face blocks plus the order in which the surface was created.

The current enumeration for Analytic_Surface_Type in the C++ API is:

```
enum ContactSearch::AnalyticSurface_Type{
  PLANE=1, SPHERE=2, CYLINDER_INSIDE=3, CYLINER_OUTSIDE=4 };
```

3.3.1 Adding an Analytic_Surface

The interface to add an Analytic_Surface is:

```
C++      ContactErrorCode ContactSearch::Add_Analytic_Surface(
                   ContactSearch::AnalyticSurface_Type as_type,
                   const double* as_data );

C        FORTRAN(add_analytic_surface)(
                   int* as_type,
                   double* as_data,
                   int* error );

Fortran  add_analytic_surface(
                   as_type,
                   as_data,
                   error )
```

where

as_type is the type of the analytic surface from the ContactSearch::AnalyticSurface_Type enum.

as_data is an array dependent on the type of surface being added. The Analytic_Surface PLANE is described by a point and a normal vector. The Analytic_Surface SPHERE is described by its center and a radius. Two types of cylindrical surfaces are supported: CYLINDER_INSIDE & CYLINDER_OUTSIDE. CYLINDER_INSIDE is intended as a cylindrical container which will define interactions to keep all nodes inside the cylinder. CYLINDER_OUTSIDE is intended as a post which will define interactions to keep all nodes outside the cylinder. Both types of cylindrical surfaces are described by a center point, an axial direction, and a length (see Figure 13). Table 8 gives a complete description of the array data for each Analytic_Surface type.

error is the return error code for the C and Fortran APIs.

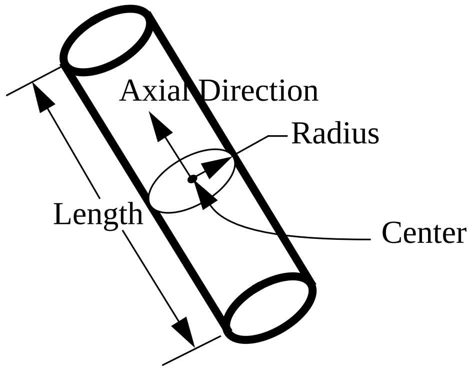


Figure 13 Analytic Cylindrical Surfaces

Table 8 C++ Data Description for Analytic_Surfaces

	Plane	Sphere	Cylinder_ Inside	Cylinder_ Outside
as_data[0]	X-Coordinate of Point	X-Coordinate of Center	X-Coordinate of Center	X-Coordinate of Center
as_data[1]	Y-Coordinate of Point	Y-Coordinate of Center	Y-Coordinate of Center	Y-Coordinate of Center
as_data[2]	Z-Coordinate of Point	Z-Coordinate of Center	Z-Coordinate of Center	Z-Coordinate of Center
as_data[3]	X-Component of Normal Vector	Radius	X-Component of Axial Vector	X-Component of Axial Vector
as_data[4]	Y-Component of Normal Vector		Y-Component of Axial Vector	Y-Component of Axial Vector
as_data[5]	Z-Component of Normal Vector		Z-Component of Axial Vector	Z-Component of Axial Vector
as_data[6]			Radius	Radius
as_data[7]			Length	Length

3.3.2 Setting the Analytic_Surface Configuration

The following interface updates the configuration(s) for an Analytic_Surface. This method has not yet been implemented in ACME, and returns an error if called.

```
C++      ContactErrorCode
         ContactSearch::Set_Analytic_Surface_Configuration(
                    int as_id,
                    const double* as_data );

C        FORTRAN(set_analytic_surface_configuration)(
                    int* as_id,
                    double* as_data,
                    int* error );

Fortran  set_analytic_surface_configuration(
                    as_id,
                    as_data,
                    error )
```

where

as_id is the ACME ID for the Analytic_Surface.
as_data is described in Table 8.
error is the return error code for the C and Fortran APIs.

3.4 Node_Block Data

Currently, the only valid type of Node_Block is NODE. Future releases of ACME will include NODE_WITH_SLOPE and NODE_WITH_RADIUS.

3.4.1 Setting the Node_Block Configuration

The following interface allows the host code to specify the configuration(s) for the nodes by Node_Block. This function can be called at any time but *must* be called prior to the first search. For a one-configuration search, only the current configuration needs to be specified. For two-configuration searches, both current and predicted configurations must be specified. This function should be called every time the nodal positions in the host code are updated. The prototype for this function is:

```
C++      ContactErrorCode
         ContactSearch::Set_Node_Block_Configuration(
                    ContactSearch::ContactNode_Configuration
                       config_type,
                    int node_block_id,
                    const double* positions );

C        FORTRAN(set_node_block_configuration)(
                    int* config_type,
                    int* node_block_id,
                    double* positions,
                    int* error );
```

```
Fortran  set_node_block_configuration(
                   config_type,
                   node_block_id,
                   positions,
                   error )
```

where:

config_type is an enumeration in the C++ API for the configuration:

```
     enum ContactSearch::ContactNode_Configuration {
        CURRENT_CONFIG=1, PREDICTED_CONFIG=2 };
```

node_block_id is the ACME ID for the Node_Block.

positions is an array that holds the nodal positions for every node in the Node_Block.The data in this array is ordered by x, y and z locations of node 1, followed by x, y and z locations of node 2, etc.

error is the return error code for the C and Fortran APIs.

3.4.2 Setting the Node_Block Kinematic Constraints

The following function informs the ContactSearch object about kinematic constraints for the nodes. If these are specified, the interactions are made consistent with the constraints. Also, the ContactTDEnforcement object computes contact forces that are consistent with these constraints.

```
C++      ContactErrorCode
         ContactSearch::Set_Node_Block_Kinematic_Constraints(
                   int node_block_id,
                   const int* constraints_per_node,
                   const double* constraint_vector );

C        FORTRAN(set_node_block_kin_cons)(
                   int* node_block_id,
                   int* constraints_per_node,
                   double* constraint_vector,
                   int* error );

Fortran  set_node_block_kin_cons(
                   node_block_id,
                   constraints_per_node,
                   constraint_vector,
                   error )
```

where

node_block_id is the ACME ID for this Node_Block

constraints_per_node is how many degrees of freedom are constrained (i.e., 0, 1, 2 or 3).

constraint_vector is a vector for each node that describes the constraint direction. If constraints_per_node is 0 or 3, this vector should be set to 0. If constraints_per_node is 1, this vector should be the constrained direction. If constraints_per_node is 2, this vector should be the unconstrained direction.

error is the return error code for the C and Fortran APIs.

3.4.3 Setting the Node_Block Attributes

The following function will be used to add Node_Block attributes, such as the projection direction for all node types, the slope for NODE_WITH_SLOPE nodes, or the radius for NODE_WITH_RADIUS nodes. Currently, the only attribute supported is the projection direction.

```
C++      ContactErrorCode
         ContactSearch::Set_Node_Block_Attributes(
                   ContactSearch::Node_Block_Attribute attribute,
                   int node_block_id,
                   const double* attributes );

C        FORTRAN(set_node_block_attributes)(
                   int* attribute,
                   int* node_block_id,
                   double* attributes,
                   int* error );

Fortran  set_node_block_attributes(
                   attribute,
                   node_block_id,
                   attributes,
                   error )
```

where

attribute is an enumeration in the C++ API for the attribute type:

```
     enum ContactSearch::Node_Block_Attribute {
        PROJECTION_DIRECTION=0 };
```

node_block_id is the ACME ID for this Node_Block.
attributes is an array of the attribute values for this Node_Block.
error is the return error code for the C and Fortran APIs.

3.5 Search Algorithms

3.5.1 Setting the Search Option

By default, both multiple interactions and normal smoothing options are inactive. The following function should be called to activate, deactivate, and control multiple interactions and normal smoothing.

```
C++      ContactErrorCode ContactSearch::Set_Search_Option(
                   ContactSearch::Search_Option option,
                   ContactSearch::Search_Option_Status status,
                   double* data );

C        FORTRAN(set_search_option)(
                   int* option,
                   int* status,
                   double* data,
                   int* error );
```

```
Fortran  set_search_option(
                   option,
                   status,
                   data,
                   error )
```

where

option is an enumeration in the C++ API:

```
enum ContactSearch::Search_Option {
   MULTIPLE_INTERACTIONS=0,
   NORMAL_SMOOTHING=1};
```

status is another enumeration:

```
enum ContactSearch::Search_Option_Status {
   INACTIVE=0,
   ACTIVE=1};
```

data is an array whose first member contains the angle above which the edge between faces is considered to be sharp instead of non-sharp (rounded), and whose second and third members (valid only for the NORMAL_SMOOTHING option) contain the distance in isoparametric coordinates over which normal smoothing is calculated and the smoothing resolution algorithm, respectively. The integer specifying the smoothing resolution algorithm can take the values USE_NODE_NORMAL=0 or USE_EDGE_BASED_NORMAL=1. See the section on Normal Smoothing in the introduction for more information about the smoothing resolution algorithm.

error is the return error code for the C and Fortran APIs.

3.5.2 Performing a Static 1-Configuration Search

The following function performs a static 1-configuration search and can be called only after a current configuration has been specified.

```
C++      ContactErrorCode
         ContactSearch::Static_Search_1_Configuration();

C        FORTRAN(static_search_1_configuration)(
                   int* error );

Fortran  static_search_1_configuration(
                   error );
```

where

error is the return error code for the C and Fortran APIs.

3.5.3 Performing a Static 2-Configuration Search

The following function performs a static 2-configuration search and can be called only if both current and predicted configurations have been specified.

```
C++      ContactErrorCode
         ContactSearch::Static_Search_2_Configuration();
```

```
C        FORTRAN(static_search_2_configuration)(
                   int* error );

Fortran  static_search_2_configuration(
                   error )
```

where

error is the return error code for the C and Fortran APIs.

3.5.4 Performing a Dynamic 2-Configuration Search

The following function performs a dynamic 2-configuration search and can be called only if both the current and predicted configurations have been specified.

```
C++      ContactErrorCode
         ContactSearch::Dynamic_Search_2_Configuration();

C        FORTRAN(dynamic_search_2_configuration)(
                   int* error );

Fortran  dynamic_search_2_configuration(
                   error )
```

where

error is the return error code for the C and Fortran APIs.

3.5.5 Performing a Dynamic Augmented 2-Configuration Search

The following function performs a dynamic augmented 2-configuration search and can be called only if both the current and predicted configurations have been specified and a ContactTDEnforcement object has been registered with the search.

```
C++      ContactErrorCode
         ContactSearch::Dynamic_Search_Augmented_2_Configuration(
                   double* mass,
                   double dt_old,
                   double dt );

C        FORTRAN(dynamic_search_aug_2_config)(
                   double* mass,
                   double* dt_old,
                   double* dt,
                   int* error );

Fortran  dynamic_search_aug_2_config(
                   mass,
                   dt_old,
                   dt,
                   error )
```

where

mass is an array that gives the mass of each node.
dt_old is the time step for the previous step.
dt is the time step for the current time step.
error is the return error code for the C and Fortran APIs.

3.6 Interactions

The functions in this section allow the host code to extract the interactions from the ContactSearch object. Typically, the host code should first determine how much memory is needed to hold the interactions before extracting the interactions.

3.6.1 Getting the Size of NodeFace_Interactions

The following function allows the host code to determine how many NodeFace_Interactions are currently defined in a ContactSearch object and the data size for each interaction.

```
C++      void ContactSearch::Size_NodeFace_Interactions(
                    int& number_of_interactions,
                    int& nfi_data_size );

C        FORTRAN(size_nodeface_interactions)(
                    int* number_of_interactions,
                    int* nfi_data_size );

Fortran  size_nodeface_interactions(
                    number_of_interactions,
                    nfi_data_size )
```

where

number_of_interactions is the number of active NodeFace_Interactions that will be returned by the function Get_NodeFace_Interactions (see the next section).
nfi_data_size is the number of double precision values returned for each interaction.

3.6.2 Extracting NodeFace_Interactions

The following function allows the host code to extract the active NodeFace_Interactions from the ContactSearch object. The prototype for this function is:

```
C++      void ContactSearch::Get_NodeFace_Interactions(
                    int* node_block_ids,
                    int* node_indexes_in_block,
                    int* node_entity_keys,
                    int* face_block_ids,
                    int* face_indexes_in_block,
                    int* face_procs,
                    double* nfi_data );
```

```
C        FORTRAN(get_nodeface_interactions)(
                    int* node_block_ids,
                    int* node_indexes_in_block,
                    int* node_entity_keys,
                    int* face_block_ids,
                    int* face_indexes_in_block,
                    int* face_procs,
                    double* nfi_data );

Fortran  get_nodeface_interactions(
                    node_block_ids,
                    node_indexes_in_block,
                    node_entity_keys,
                    face_block_ids,
                    face_indexes_in_block,
                    face_procs,
                    nfi_data )
```

where

node_block_ids is an array (of length number_of_interactions) that contains the Node_Block ID for the node in each interaction.
node_indexes_in_block is an array (of length number_of_interactions) that contains the index in the Node_Block (using Fortran indexing conventions) for the node in each interaction.
node_entity_keys is an array (of length number_of_interactions) that contains the node entity key for this interaction.
face_block_ids is an array (of length number_of_interactions) that contains the Face_Block ID for the face in each interaction.
face_indexes_in_block is an array (of length number_of_interactions) that contains the index in the Face_Block (using Fortran indexing conventions) for the face in each interaction.
face_procs is an array (of length number_of_interactions) that contains the processor that owns the face in each interaction.
nfi_data is an array (of length number_of_interactions*nfi_data_size) that contains the data for each interaction (see Section 1.3.1). The data for each interaction is contiguous (i.e., the first nfi_data_size locations contain the data for the first interaction).

3.6.3 Getting the Size of NodeSurface_Interactions

The following function allows the host code to determine how many interactions are currently defined in a ContactSearch object and the data size for each interaction.

```
C++      void ContactSearch::Size_NodeSurface_Interactions(
                    int& number_of_interactions,
                    int& nsi_data_size );

C        FORTRAN(size_nodesurface_interactions)(
                    int* number_of_interactions,
                    int* nsi_data_size );

Fortran  size_nodesurface_interactions(
                    number_of_interactions,
                    nsi_data_size )
```

where

number_of_interactions are the number of active NodeSurface_Interactions that will be returned by the function Get_NodeSurface_Interactions (see the next section).
nsi_data_size is the number of double precision values returned for each interaction.

3.6.4 Extracting NodeSurface_Interactions

The following function allows the host code to extract the active NodeSurface_Interactions from the ContactSearch object. The prototype for this function is:

```
C++      void ConstactSearch::Get_NodeSurface_Interactions(
                   int* node_block_ids,
                   int* node_indexes_in_block,
                   int* analyticsurface_ids,
                   double* nsi_data );

C        FORTRAN(get_nodesurface_interactions)(
                   int* node_block_ids,
                   int* node_indexes_in_block,
                   int* analyticsurface_ids,
                   double* nsi_data );

Fortran  get_nodesurface_interactions(
                   node_block_ids,
                   node_indexes_in_block,
                   analyticsurface_ids,
                   nsi_data )
```

where

node_block_ids is an array (of length number_of_interactions) that contains the Node_Block ID for the node in each interaction.
node_indexes_in_block is an array (of length number_of_interactions) that contains the index in the Node_Block (using Fortran indexing conventions) for the node in each interaction.
analyticsurface_ids is an array (of length number_of_interactions) that contains the ID of the Analytic_Surface for each interaction.
nsi_data is an array (of length number_of_interactions*nsi_data_size) that contains the data for each interaction (see Section 1.3.2). The data for each interaction is contiguous (i.e., the first nsi_data_size locations contain the data for the first interaction).

3.6.5 Getting the Size of FaceFace_Interactions

The following function allows the host code to determine how many FaceFace_Interactions are currently defined in a ContactSearch object and the data size for all interactions.

```
C++      void ContactSearch::Size_FaceFace_Interactions(
                   int& number_of_interactions,
                   int& ffi_data_size );

C        FORTRAN(size_faceface_interactions)(
                   int* number_of_interactions,
                   int* ffi_data_size );

Fortran  size_faceface_interactions(
                   number_of_interactions,
                   ffi_data_size )
```

where

number_of_interactions is the number of active FaceFace_Interactions that will be returned by the function Get_FaceFace_Interactions (see the next section).

ffi_data_size is the number of double precision values returned for the entire set of FaceFace_Interactions.

3.6.6 Extracting FaceFace_Interactions

The following function allows the host code to extract the active FaceFace_Interactions from the ContactSearch object. The prototype for this function is:

```
C++      void ContactSearch::Get_FaceFace_Interactions(
                   int* slave_face_block_ids,
                   int* slave_face_indexes_in_block,
                   int* master_face_block_ids,
                   int* master_face_indexes_in_block,
                   int* master_face_procs,
                   int* ffi_index,
                   double* ffi_data );

C        FORTRAN(get_faceface_interactions)(
                   int* slave_face_block_ids,
                   int* slave_face_indexes_in_block,
                   int* master_face_block_ids,
                   int* master_face_indexes_in_block,
                   int* master_face_procs,
                   int* ffi_index,
                   double* ffi_data );

Fortran  get_faceface_interactions(
                   slave_face_block_ids,
                   slave_face_indexes_in_block,
                   master_face_block_ids,
                   master_face_indexes_in_block,
                   master_face_procs,
                   ffi_index,
                   ffi_data)
```

where

slave_face_block_ids is an array (of length number_of_interactions) that contains the Face_Block ID for the slave face in each interaction.
slave_face_indexes_in_block is an array (of length number_of_interactions) that contains the index in the Face_Block (using Fortran indexing conventions) for the slave face in each interaction.
master_face_block_ids is an array (of length number_of_interactions) that contains the Face_Block ID for the master face in each interaction.
master_face_indexes_in_block is an array (of length number_of_interactions) that contains the index in the Face_Block (using Fortran indexing conventions) for the master face in each interaction.
master_face_procs is an array (of length number_of_interactions) that contains the processor that owns the master_face in each interaction.
ffi_index is an array (of length number_of_interactions) that contains the offset into the ffi_data array for the data for each interaction (i.e., the data for interaction j begins at ffi_data[ffi_index[j]]).
ffi_data is an array (of length ffi_data_size) that contains the data for each interaction (see Section 1.3.3). The data for each interaction is contiguous.

3.6.7 Getting the Size of FaceCoverage_Interactions

The following function allows the host code to determine how many FaceCoverage_Interactions are currently defined in a ContactSearch object and the data size for all the interactions.

```
C++      void ContactSearch::Size_FaceCoverage_Interactions(
                   int& number_of_interactions,
                   int& fci_data_size );

C        FORTRAN(size_facecoverage_interactions)(
                   int* number_of_interactions,
                   int* fci_data_size );

Fortran  size_facecoverage_interactions(
                   number_of_interactions,
                   fci_data_size )
```

where

number_of_interactions is the number of active FaceCoverage_Interactions that will be returned by the function Get_FaceCoverage_Interactions (see the next section).
fci_data_size is the number of double precision values returned for the entire set of FaceCoverage_Interactions.

3.6.8 Extracting FaceCoverage_Interactions

The following function allows the host code to extract the active FaceCoverage_Interactions from the ContactSearch object. The prototype for this function is:

```
C++      void ContactSearch::Get_FaceCoverage_Interactions(
                   int* face_block_ids,
                   int* face_indexes_in_block,
                   int* fci_index,
                   double* fci_data );

C        FORTRAN(get_facecoverage_interactions)(
                   int* face_block_ids,
                   int* face_indexes_in_block,
                   int* fci_index,
                   double* fci_data );

Fortran  get_facecoverage_interactions)(
                   face_block_ids,
                   face_indexes_in_block,
                   fci_index,
                   fci_data );
```

where

face_block_ids is an array (of length number_of_interactions) that contains the Face_Block ID for the face in each interaction.
face_indexes_in_block is an array (of length number_of_interactions) that contains the index in the Face_Block (using Fortran indexing conventions) for the face in each interaction.
fci_index is an array (of length number_of_interactions) that contains the offset into the fci_data array for the data for each interaction (i.e., the data for interaction j begins at fci_data[fci_index[j]]).
fci_data is an array (of length fci_data_size) that contains the data for each interaction (see Section 1.3.4). The data for each interaction is contiguous.

3.6.9 Deleting Interactions

The following function permits the host code to delete all previously found interactions before conducting a new search. This function is of particular use when a single search object conducts two different enforcements. For example, if an analysis uses both ContactGapRemoval and ContactTDEnforcement with a single ContactSearch object, then the interactions used for ContactGapRemoval can negatively affect the ContactTDEnforcement. In this case, it is better to delete the interactions determined for ContactGapRemoval before doing a search for ContactTDEnforcement.

```
C++      ContactErrorCode
         ContactSearch::Delete_All_Interactions();

C        FORTRAN(delete_all_interactions)();

Fortran  delete_all_interactions()
```

3.7 Registering an Enforcement Object with the Search

There are currently two reasons why the search object needs to know about an associated enforcement object. The first is to allow the enforcement data to be added to the plot data base (see Section 2.5). The plot database can only be created if ACME was compiled with ExodusII support (i.e., noexo was not defined). The second reason is to allow the dynamic augmented 2-configuration search (see Section 1.2.4) to get the data it needs from a ContactTDEnforcement object to construct the augmented configuration.

The following function may be called for either a ContactTDEnforcement or a ContactGapRemoval object. The ContactTDEnforcement object will add the contact force to the plotting database and the ContactGapRemoval object will add the displacement correction to the plotting database; both objects will store the data in variables called EnfVarx, EnfVary, and EnfVarz. Note that the C and Fortran API function prototypes are actually in Enforcement_Interface.h instead of Search_Interface.h.

```
C++      void Contact_Search::Register_Enforcement(
                    ContactEnforcement* enforcement );

C        FORTRAN(reg_td_enforcement_w_search)();
         FORTRAN(reg_gap_removal_w_search)();

Fortran  reg_td_enforcement_w_search();
         reg_gap_removal_w_search();
```

where

enforcement is either a ContactTDEnforcement object or a ContactGapRemoval object.

4. Gap Removal Enforcement Functions

The gap removal enforcement will compute a displacement increment needed to remove overlaps, as discussed in Section 1.6. This section describes functions that construct and operate on ContactGapRemoval "objects." For the C++ API, these are true objects permitted by the object-oriented capabilities of the language. In the C and Fortran APIs, these functions create and operate on a ContactGapRemoval "object," only one of which is currently allowed.

In each section delineating the ACME API functions (Sections 2, 3, 4, and 5), the different forms for the C++, C, and Fortran syntax are presented together for each function call. The C++ API uses the full object-oriented capabilities of the language. On the other hand, the C and Fortran APIs, which in actuality have been combined into a single interface, are a collection of functions that have a pure C interface and can be called from either C or Fortran rountines. The FORTRAN macro that surrounds all calls in the C syntax converts the function by appending an underscore to the end of the function name, if appropriate. Because of this, all data in the C API must be passed by address, not by value. For Fortran, there exists no capability to pass data by value, so simply specifying the name of the variable or array will allow it to be passed appropriately.

The Enforcement_Interface.h header file, located in the ACME enforcement directory, includes the prototypes for the C and Fortran functions described in this chapter, and the ContactGapRemoval.h file includes the C++ prototypes. Enumerations for symbolic types used in the C++ API are also found in ContactEnforcement.h and ContactGapRemoval.h; these indicate the acceptable integral values that may be used in the C and Fortran APIs.

4.1 Constructing a ContactGapRemoval Object

There is one general purpose constructor for the ContactGapRemoval object. There are two restart constructors for this object. They are of the same form as all the other objects, as discussed in Sections 1.9, 2.3 and 2.4, so they will not be discussed further in this section.

The prototype for the initial ContactGapRemoval constructor is:

```
C++      ContactGapRemoval::ContactGapRemoval(
                   double* Enforcement_Data,
                   ContactSearch* search,
                   ContactSearch::ContactErrorCode& error );

C        FORTRAN(build_gap_removal)(
                   double* Enforcement_Data,
                   int* error );

Fortran  build_gap_removal(
                   double* Enforcement_Data,
                   int* error );
```

where

Enforcement_Data is a real array (of length 1*(number of entity keys)*(number of entity keys)) that stores the kinematic partition factor. It is structured [n_key*number_entity_keys+f_key] where n_key is the node key and f_key is the face key. The kinematic partition factor controls the master/slave relationship between two entities as described in Section 1.5.

search is the ContactSearch object from which the topology, interactions, and configurations are obtained.

error is the error code (described in Section 1.7) that will reflect any errors that were detected.

4.2 Computing the Gap Removal Displacements

This member function computes the displacement increments necessary to remove any initial gaps that are contained in the ContactSearch object topology. A static 1-configuration search should be used to define the interactions prior to calling this member function (regardless of the type of mechanics being solved).

```
C++      ContactErrorCode ContactGapRemoval::Compute_Gap_Removal(
                    double* displ_cor);

C        FORTRAN(compute_gap_removal)(
                    double* displ_cor,
                    int* error );

Fortran  compute_gap_removal(
                    displ_cor,
                    error )
```

where

displ_cor is the displacement correction needed at each node to remove the initial gaps.

4.3 Destroying a ContactGapRemoval Object

```
C++      ~ContactGapRemoval();

C        FORTRAN(cleanup_gap_removal)();

Fortran  cleanup_gap_removal()
```

5. Explicit Transient Dynamic Enforcement Functions

This section describes functions that construct and operate on ContactTDEnforcement "objects." For the C++ API, these are true objects permitted by the object-oriented capabilities of the language. In the C and Fortran APIs, these functions create and operate on a ContactTDEnforcement "object," only one of which is currently allowed.

In each section delineating the ACME API functions (Sections 2, 3, 4, and 5), the different forms for the C++, C, and Fortran syntax are presented together for each function call. The C++ API uses the full object-oriented capabilities of the language. On the other hand, the C and Fortran APIs, which in actuality have been combined into a single interface, are a collection of functions that have a pure C interface and can be called from either C or Fortran rountines. The FORTRAN macro that surrounds all calls in the C syntax converts the function by appending an underscore to the end of the function name, if appropriate. Because of this, all data in the C API must be passed by address, not by value. For Fortran, there exists no capability to pass data by value, so simply specifying the name of the variable or array will allow it to be passed appropriately.

The Enforcement_Interface.h header file, located in the ACME enforcement directory, includes the prototypes for the C and Fortran functions described in this chapter, and the ContactTDEnforcement.h file includes the C++ prototypes. Enumerations for symbolic types used in the C++ API are also found in ContactEnforcement.h and ContactTDEnforcement.h; these indicate the acceptable integral values that may be used in the C and Fortran APIs.

5.1 Creating a ContactTDEnforcement Object

There is one general purpose constructor for the ContactTDEnforcement object. There are two restart constructors for this object. They are of the same form as all the other objects, as discussed in Sections 1.9, 2.3 and 2.4, so they will not be discussed further in this section.

The prototype for the initial ContactTDEnforcement constructor is:

```
C++      ContactTDEnforcement::ContactTDEnforcement(
                   double* Enforcement_Data,
                   ContactSearch* search,
                   ContactSearch::ContactErrorCode& error );

C        FORTRAN(build_td_enforcement)(
                   double* Enforcement_Data,
                   int* error );

Fortran  build_td_enforcement(
                   Enforcement_Data,
                   error )
```

where

Enforcement_Data is a real array (of length 2*(number of entity keys)*(number of entity keys)) that stores the kinematic partition factor and the friction model id. It is structured [(n_key*number_entity_keys+f_key)*size_data_per_pair+variable_index] where n_key is the node key and f_key is the face key. The kinematic partition factor controls the master/slave relationship between two entities. The friction model id pertains to the constitutive behavior of the interactions and is described in the following section.

search is the ContactSearch object from which the topology, interactions, and configurations are obtained.

error is the error code (described in Section 1.7) that will reflect any errors that were detected.

5.2 Defining Enforcement Models

The contact behavior is controlled by enforcement models. Three types of enforcement models are currently supported; FRICTIONLESS, CONSTANT_FRICTION, and TIED. For the C++ API, please note that Add_Enforcement_Model is a function inherited by ContactTDEnforcement. To define the enforcement model to be used, the following function must be called:

```
C++      ContactSearch::ContactErrorCode
         ContactEnforcement::Add_Enforcement_Model(
                   Enforcement_Model_Types type,
                   int* ID,
                   int* integer_data,
                   double* real_data );

C        FORTRAN(td_add_enf_model)(
                   int* type,
                   int* id,
                   int* integer_data,
                   double* real_data,
                   int* error );

Fortran  td_add_enf_model (
                   type,
                   id,
                   integer_data,
                   real_data,
                   error )
```

where

type is the enforcement model type (as shown in Table 9).
id is a positive integer identifier for the model.
integer_data is an array of integer data that is particular to the model (as shown in Table 9).
real_data is an array of real data that is particular to the model (as shown in Table 9).
error is the return error code for the C and Fortran APIs.

Table 9 Transient Dynamic Enforcement Models and Data

Type	Integer Data	Real Data
TD_FRICTIONLESS = 1	None	None
TD_CONSTANT_FRICTION=2	None	Friction Coefficient
TD_TIED=3	None	None

5.3 Computing the Contact Forces

The following member function computes the contact forces necessary to enforce the contact constraints that are contained in the ContactSearch object.

```
C++      ContactSearch::ContactErrorCode
         ContactTDEnforcement::Compute_Contact_Force(
                   double dt_old,
                   double dt,
                   double* mass,
                   double* force );

C        FORTRAN(compute_td_contact_force)(
                   double* dt_old,
                   double* dt,
                   double* mass,
                   double* force,
                   int* error );

Fortran  compute_td_contact_force(
                   dt_old,
                   dt,
                   mass,
                   force,
                   error )
```

where

dt_old is the previous time step for a central difference integrator.
dt is the current time step for a central difference integrator.
mass is an array that contains the nodal mass for each node.
force is the return array containing the computed contact force vectors for each node.
error is the return error code for the C and Fortran APIs.

5.4 Destroying a ContactTDEnforcement Object

```
C++      ~ContactTDEnforcement();

C        FORTRAN(cleanup_td_enforcement)();

Fortran  cleanup_td_enforcement()
```

6. Example

This section outlines a simple single-processor search example with multiple face types and an Analytic_Surface using the C++ interface. The only differences in using the C or Fortran interface would be calling the analogous C/Fortran functions (the data and calling sequence would be the same).

6.1 Problem Description

Consider the problem shown in Figure 14, where two bodies impact each other as well as an analytic plane. One body is discretized with 8-node hexahedral elements and the other is discretized with 4-node tetrahedral elements (the discretizations are not shown in Figure 14, however). For this example, we consider a dynamic search for NodeFace_Interactions. As previously noted, all interactions with Analytic_Surfaces are static checks, regardless of the type of search, for this version of ACME. The host code is responsible for creating a topological representation of the surface to supply to ACME. The Face_Block numbering is shown in Figure 15, the surface topology is shown in Figure 16, and the connectivities for the faces are given in Table 10.

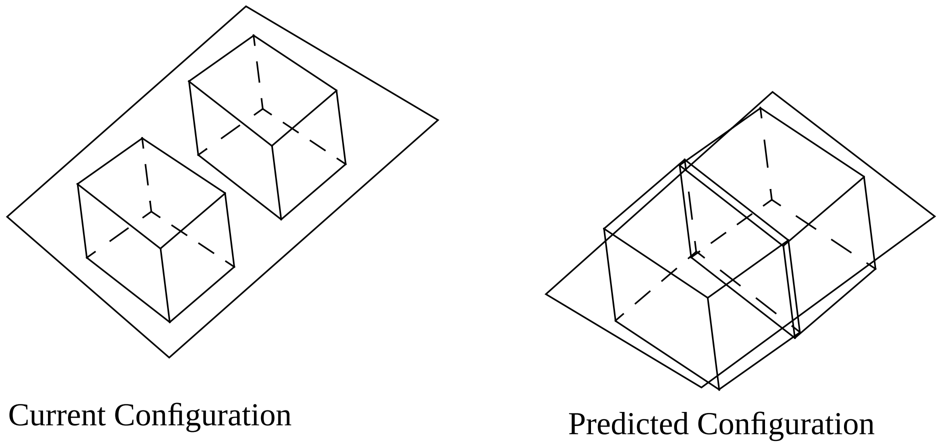


Figure 14 Example impact problem (two rectangular bodies and an Analytic_Surface)

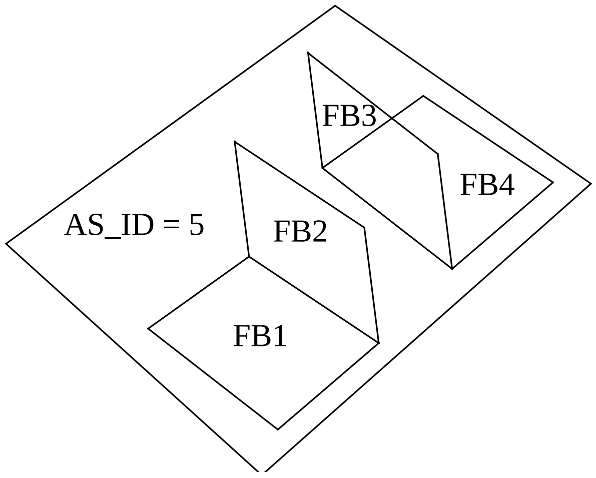


Figure 15 Face_Block Numbering for Example Problem

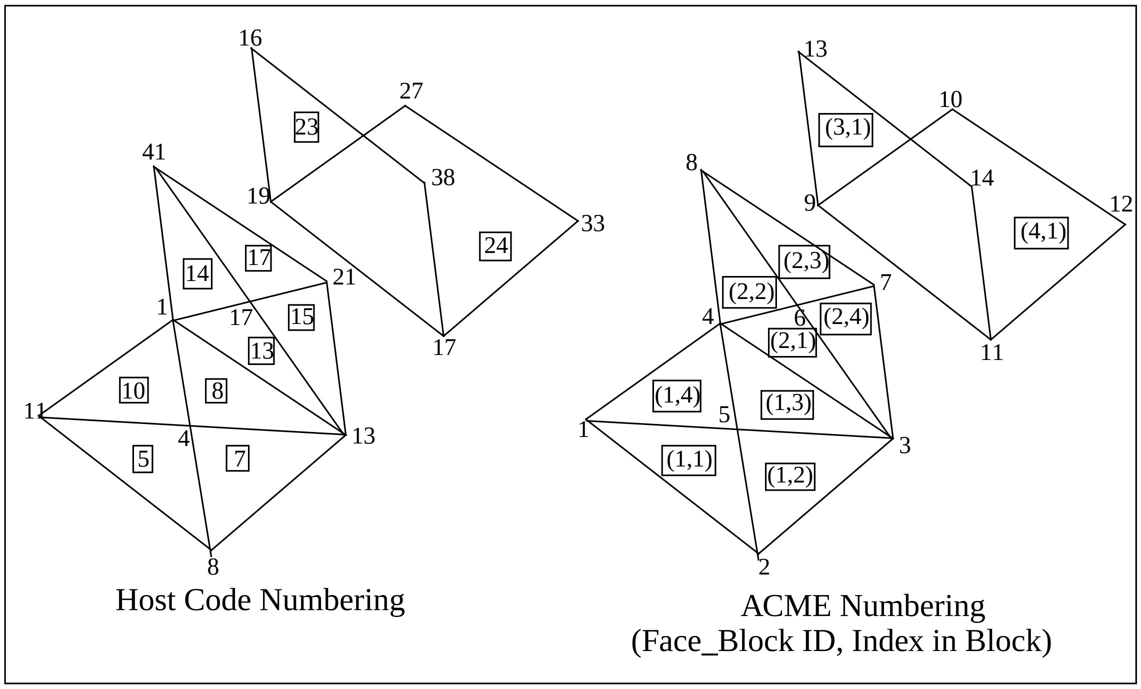


Figure 16 Surface Topology for Example Problem

Because all of the nodes are attached to faces, only one Node_Block is used, as required by the current implementation (this block will then have an ID of 1). For this example, consider the case where the user wants to specify one set of search tolerance values between the two bodies and another set between each body and the analytic plane, as well as specifying the interaction type between each. To accommodate this, the number of Face_Blocks will be four (one for the “side” face of the left body, one for the “bottom” face of the left body, one for the “side” face of the right body and one for the “bottom” face of the right body). The total number of Entity_Keys will then be 5 (one each for the Face_Blocks and an additional one for the PLANE Analytic_Surface).

Table 10 Face_Blocks for Example Problem

Host Code Face ID	Face_Block ID	Index in Block	Connectivity
5	1	1	1-5-2
7	1	2	2-5-3
8	1	3	3-5-4
10	1	4	5-1-4

Table 10 Face_Blocks for Example Problem

Host Code Face ID	Face_Block ID	Index in Block	Connectivity
13	2	1	4-6-3
14	2	2	4-8-6
17	2	3	8-7-6
15	2	4	6-7-3
23	3	1	9-11-14-13
24	4	1	9-10-12-11

6.2 Constructing a ContactSearch Object

The code fragment below represents the call (and error checking) to construct the Contact-Search object:

```
ContactSearch::ContactErrorCode error;
ContactSearch search_obj(
   dimensionality, number_of_states, number_of_entity_keys,
   number_of_node_blocks, node_block_types,
   number_of_nodes_in_blocks, node_global_ids,
   number_of_face_blocks, face_block_types,
   number_of_faces_in_block, connectivity,
   number_of_nodal_comm_partners, nodal_comm_proc_ids,
   number_of_nodes_to_partner, communication_nodes,
   mpi_communicator, error );
if( error ){ // an error occurred on some processor
   int num_err = search_obj.Number_of_Errors();
   for( int i=0 ; i<num_err ; i++ )
      cout << search_obj.Error_Message(i) << endl;
   exit(error);
}
```

The data below represent the values of the arguments in the constructor:

```
dimensionality = 3
number_of_states = 1
number_of_entity_keys = 5
number_of_node_blocks = 1
node_block_types = { NODE }
number_of_nodes_in_blocks = { 14 }
node_global_ids = { 11,8,13,1,4,17,21,41,17,33,19,27,38,16 }
number_of_face_blocks = 4
face_block_types = { TRIFACEL3, TRIFACEL3, QUADFACEL4, QUADFACEL4 }
number_of_faces_in_block = { 4, 4, 1, 1 }
connectivity = { [1, 5, 2, 2, 5, 3, 3, 5, 4, 5, 1, 4], [4, 6, 3, 4,
   8 ,6, 8, 7, 6, 6, 7, 3], [9, 11, 14, 13] , [9, 11, 12, 10] }
number_of_nodal_comm_partners = 0
```

```
nodal_comm_proc_ids = NULL
number_of_nodes_to_partner = NULL
communication_nodes = NULL
mpi_communicator = 0
```

6.3 Adding an Analytic_Surface

The next step is to add the analytic plane. Since we have already added four Face_Blocks, the ID of the PLANE Analytic_Surface will be 5. The code fragment (and error checking) to add this Analytic_Surface is:

```
error = search_obj.Add_Analytic_Surface(
   analytic_surfacetype,
   data );
if( error ){
   int num_err = search_obj.Number_of_Errors();
   for( int i=0 ; i<num_err ; i++ )
      cout << search_obj.Error_Message( i ) << endl;
   exit(error);
}
```

The data needed to add the Analytic_Surface are (see Table 8 for a description of the data):

```
analyticsurface_type = PLANE
data = { [0.0, 0.0, 0.0], [0.0, 1.0, 0.0] }
```

6.4 Search Data

The next step is to set the Search_Data. For this example, assume the user only wants interactions for nodes of Face_Block 2 against faces of Face_Block 3, nodes of Face_Block 3 against faces of Face_Block 2 and nodes of Face_Blocks 1 and 4 against the PLANE Analytic_Surface. We will use a Search_Normal_Tolerance of 0.01 for interactions between the two bodies and a Search_Normal_Tolerance of 0.1 for the bodies against the PLANE Analytic_Surface. We will use Search_Tangential_Tolerance values of half the respective Search_Normal_Tolerance values. Currently, a node only has one entity key (this is a limitation of the current implementation and will be addressed in a future release). The entity_key assigned to the node is from the first face it is connected to. As a result of this limitation, we must also allow interactions to be defined between nodes from face block 1 to interact with faces from face block 3 and nodes from face block 4 to interact with faces from face block 2. The call to add these data is:

```
search_obj.Set_Search_Data( Search_Data );
```

The search data array, with 2 x 5 x 5 values, is:

```
Search_Data = {
   0, 0.01, 0.005 // FB1 nodes against FB1 faces
   0, 0.01, 0.005 // FB2 nodes against FB1 faces
   0, 0.01, 0.005 // FB3 nodes against FB1 faces
```

```
      0, 0.01, 0.005 // FB4 nodes against FB1 faces
      0, 0.01, 0.005 // Analytic Plane against FB1 faces (don’t exist)
      0, 0.01, 0.005 // FB1 nodes against FB2 faces
      0, 0.01, 0.005 // FB2 nodes against FB2 faces
      1, 0.01, 0.005 // FB3 nodes against FB2 faces
      1, 0.01, 0.005 // FB4 nodes against FB2 faces
      0, 0.01, 0.005 // Analytic Plane against FB2 faces (don’t exist)
      1, 0.01, 0.005 // FB1 nodes against FB3 faces
      1, 0.01, 0.005 // FB2 nodes against FB3 faces
      0, 0.01, 0.005 // FB3 nodes against FB3 faces
      0, 0.01, 0.005 // FB4 nodes against FB3 faces
      0, 0.01, 0.005 // Analytic Plane against FB4 faces (don’t exist)
      0, 0.01, 0.005 // FB1 nodes against FB4 faces
      1, 0.01, 0.005 // FB2 nodes against FB4 faces
      0, 0.01, 0.005 // FB3 nodes against FB4 faces
      0, 0.01, 0.005 // FB4 nodes against FB4 faces
      0, 0.01, 0.005 // Analytic Plane against FB4 faces (don’t exist)
      1, 0.1, 0.05 // FB1 nodes against Analytic Plane
      0, 0.1, 0.05 // FB2 nodes against Analytic Plane
      0, 0.1, 0.05 // FB3 nodes against Analytic Plane
      1, 0.1, 0.05 // FB4 nodes against Analytic Plane
      0, 0.1, 0.05 } // Analytic Plane against Analytic Plane
```

6.5 Setting the Search Options

For this example, multiple interaction definition is necessary but normal smoothing is not needed. A value of 30 degrees will be used for the SHARP_NON_SHARP_ANGLE. The code fragment to activate multiple interactions is

```
   // Activate multiple interaction
   error = Set_Search_Option(
      ContactSearch::MULTIPLE_INTERACTIONS,
      ContactSearch::ACTIVE,
      multiple_interaction_data );
      if( error ){
         int num_err = search_obj.Number_of_Errors();
         for( int i=0 ; i<num_err ; i++ )
            cout << search_obj.Error_Message( i ) << endl;
         exit(error);
      }
```

where multiple_interaction_data is a pointer to the SHARP_NON_SHARP_ANGLE which has been set to 30 degrees. The code fragment to deactivate normal smoothing is

```
   // Deactivate normal smoothing
   error = Set_Search_Option(
      ContactSearch::NORMAL_SMOOTHING,
      ContactSearch::INACTIVE,
      dummy );
      if( error ){
         int num_err = search_obj.Number_of_Errors();
```

```
          for( int i=0 ; i<num_err ; i++ )
             cout << search_obj.Error_Message( i ) << endl;
          exit(error);
       }
```

Since normal smoothing is being deactivated, dummy is a pointer to double but will never be dereferenced so its value is irrelevant.

6.6 Specifying Configurations

At this point the topology is completely specified. The search object can be used to compute the interactions once the configurations are specified. Since we are going to perform a dynamic search, we need to specify the current and predicted configurations for the Node_Blocks (in this case only one block). The code fragment to set the configurations is:

```
// Supply the current position
for( int iblk=1 ; iblk<=number_of_node_blocks ; iblk++ ){
   error = search_obj.Set_Node_Block_Configuration(
      ContactSearch::CURRENT_CONFIG,
      iblk,
      current_positions[iblk-1] );
   if( error ){
      int num_err = search_obj.Number_of_Errors();
      for( int i=0 ; i<num_err ; i++ )
         cout << search_obj.Error_Message( i ) << endl;
      exit(error);
   }
   // Supply the predicted position
   error = search_obj.Set_Node_Block_Configuration(
      ContactSearch::PREDICTED_CONFIG,
      iblk,
      predicted_positions[iblk-1] );
   if( error ){
      int num_err = search_obj.Number_of_Errors();
      for( int i=0 ; i<num_err ; i++ )
         cout << search_obj.Error_Message( i ) << endl;
      exit(error);
   }
}
```

The current and predicted positions for the nodes are shown in Table 11.

Table 11 Current and Predicted Positions for Example Problem

Node	Current Position	Predicted Position
1	{-1.1 0.1 0.0}	{-0.9 -0.1 0.0}
2	{ -1.1 0.1 1.0}	{-0.9 -0.1 1.0 }
3	{ -0.1 0.1 1.0}	{ 0.1 -0.1 1.0}

Table 11 Current and Predicted Positions for Example Problem

Node	Current Position	Predicted Position
4	{ -0.1 0.1 0.0}	{ 0.1 -0.1 0.0}
5	{ -0.6 0.1 0.5}	{ -0.4 -0.1 0.5}
6	{ -0.1 0.6 0.6}	{ 0.1 0.4 0.6}
7	{ -0.1 1.1 1.0}	{ 0.1 0.9 1.0}
8	{ -0.1 1.1 0.0}	{ 0.1 0.9 0.0}
9	{0.1 0.1 0.0}	{ -0.1 -0.1 0.0}
10	{1.1 0.1 0.0}	{0.9 -0.1 0.0 }
11	{0.1 0.1 1.0}	{ -0.1 -0.1 1.0}
12	{1.1 0.1 1.0}	{0.9 -0.1 1.0 }
13	{0.1 1.1 0.0}	{-0.1 0.9 0.0 }
14	{0.1 1.1 1.0}	{ -0.1 0.9 1.0}

6.7 Performing the Search

The search can now be performed with the following code fragment:

```
error = search_obj.Dynamic_Search_2_Configuration();
if( error ){
   cout << “Error in Dynamic_Search:: Error Code = “
      << error << endl;
   int num_err = search_obj.Number_of_Errors();
   for( i=0 ; i<num_err ; i++ )
      cout << search_obj.Error_Message(i) << endl;
   exit(error);
}
```

6.8 Extracting Interactions

The following coding will extract both the NodeFace_Interactions and the NodeSurface_Interactions:

```
// Get the NodeFace_Interactions
int number_of_NFIs, NFI_data_size;
search_obj.Size_NodeFace_Interactions(
   number_of_NFIs,
   NFI_data_size);
if( number_of_NFIs ){
        int* NFI_node_block_ids = new int[number_of_NFIs];
        int* NFI_node_indexes_in_block = new int[number_of_NFIs];
        int* NFI_face_block_ids = new int[number_of_NFIs];
        int* NFI_face_indexes_in_block = new int[number_of_NFIs;]
        int* NFI_face_procs = new int[number_of_NFIs];
        double* NFI_data = new double[number_of_NFIs*NFI_data_size];
        search.Get_NodeFace_Interactions(NFI_node_block_ids,
           NFI_node_indexes_in_block,NFI_face_block_ids,
           NFI_face_indexes_in_block,NFI_face_procs,NFI_data);
     }

     // Get the NodeSurface_Interactions
     int number_of_NSIs, NSI_data_size;
     search_obj.Size_NodeSurface_Interactions(
        number_of_NSIs,
        NSI_data_size );
     if( number_of_NSIs ){
        int* NSI_node_block_ids = new int[number_of_NSIs];
        int* NSI_node_indexes_in_block = new int[number_of_NSIs];
        int* NSI_analyticsurface_ids = new int[number_of_NSIs];
        double* NSI_data = new double[number_of_NSIs*NSI_data_size];
        search.Get_NodeSurface_Interactions(NSI_node_block_ids,
           NSI_node_indexes, NSI_analyticsurface_ids, NSI_data );
     }
```

Table 12 gives the data for the NodeFace_Interactions and Table 13 gives the data for the NodeSurface_Interactions.

Table 12 NodeFace_Interactions for Example Problem

Node Block	Index in Block	Face Block	Index in Block	Local Coords	Gap	Unit Pushback Vector	Unit Surface Normal	Alg.
1	3	3	1	1, -1	-0.2	-1, 0, 0	-1, 0, 0	3
1	4	3	1	-1, -1	-0.2	-1, 0, 0	-1, 0, 0	3
1	6	3	1	0, 0	-0.2	-1, 0, 0	-1, 0, 0	3
1	7	3	1	1, 1	-0.2	-1, 0, 0	-1, 0, 0	3
1	8	3	1	-1, 1	-0.2	-1, 0, 0	-1, 0, 0	3
1	9	2	1	0, 0	-0.2	1, 0, 0	1, 0, 0	3
1	11	2	1	0, 0	-0.2	1, 0, 0	1, 0, 0	3
1	13	2	2	0, 1	-0.2	1, 0, 0	1, 0, 0	3
1	14	2	3	0, 1	-0.2	1, 0, 0	1, 0, 0	3

Table 13 NodeSurface_Interactions for Example Problem

Node Block	Index in Block	Surface ID	Gap	Interaction Point	Surface Normal
1	1	5	-0.1	-0.9, 0, 0	0, 1, 0
1	2	5	-0.1	-0.9, 0, 1	0, 1, 0
1	5	5	-0.1	-0.4, 0, 0.5	0, 1, 0
1	11	5	-0.1	-0.1, 0, 1	0, 1, 0
1	9	5	-0.1	-0.1, 0, 0	0, 1, 0
1	4	5	-0.1	0.1, 0, 0	0, 1, 0
1	3	5	-0.1	0.1, 0, 1	0, 1, 0
1	10	5	-0.1	0.9, 0, 0	0, 1, 0
1	12	5	-0.1	0.9, 0, 1	0, 1, 0

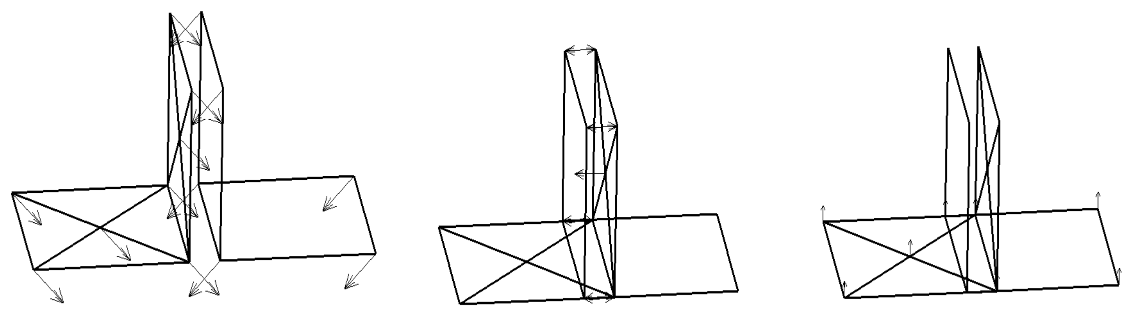
This completes the example for one time step. It is assumed the host code would take these interactions, enforce the constraints implied by these interactions and then integrate the governing equations to the next time step. At that point, the host code can supply the current and predicted configurations for the new time step and call the search again to define new interactions. This process can then be repeated until the analysis is complete.

6.9 ExodusII Output

An ExodusII output file can be created which contains the topology and interactions with the following code fragment

```
int iows = 8;
int compws = 8;
char OutputFileName[] = "contact_topology.exo";
int exodus_id=ex_create(OutputFileName,EX_CLOBBER,&compws,&iows );
if( search->Exodus_Output( exodus_id, time ) ){
   cout << "Error with exodus output" << endl;
   for( i=0 ; i<search->Number_of_Errors() ; i++ )
      cout << search->Error_Message(i) << endl;
}
ex_close( exodus_id );
```

Figure 17 shows plots from the ExodusII output for this example. The analytic plane is not shown in these plots because there is no way to include this plane in the ExodusII file.



(a) (b) (c)

Figure 17 ExodusII Output for Example Problem

a) The topology with a vector plot of displacement.
b) NodeFace_Interaction vector plot. Note the interaction vectors push back exactly to the opposing face.
c) NodeSurface_Interaction vector plot. The “top” of the vectors represent the location of the Analytic_Surface.

Appendix A: Glossary of ACME Terms

ACME - Algorithms for Contact in a Multiphysics Environment.

Analytic_Surface - A rigid surface that can be described analytically by a geometric definition (e.g., planes and spheres).

ContactErrorCode - An error code returned by all public access functions in ACME.

ContactFace_Type - The type of faces in a Face_Block, currently QUADFACEL4, QUADFACEQ8, TRIFACEL3, or TRIFACEQ6.

ContactGapRemoval - The top level object constructed by a host application to determine a displacement increment that will remove initial gaps using interactions found by the ContactSearch object.

ContactNode_Type - The type of nodes in a Node_Block, currently only NODE. (NODE_WITH_SLOPE and NODE_WITH_RADIUS not yet available in this release.)

ContactSearch - The top-level object constructed by a host application to search for topological interactions.

ContactTDEnforcement - The top level object constructed by a host application to determine forces from topological interactions found by the ContactSearch object for use in transient dynamics equations.

Dynamic 2-Configuration Search - The search algorithm that uses a combination of a dynamic intersection and closest point projection to determine interactions.

Dynamic Augmented 2-Configuration Search - The search algorithm that uses contact forces from the last time step (from a ContactTDEnforcement object) to construct an augmented predicted configuration. The algorithm then determines interactions using this configuration with a combination of a dynamic intersection and closest point projection.

Entity_Key - An identifier for a topological entity (currently node, face, or Analytic_Surface) used to extract user-specified parameters from the Search_Data array.

Face_Block - A collection of faces of the same type that have the same Entity_Key.

FaceCoverage_Interaction - A set of data returned by ACME to the host code that contains the interacting face and the data describing the interaction (the contour of the uncovered portion of the face is described by the number of edges and edge nodes of that contour).

FaceFace_Interaction - A set of data returned by ACME to the host code that contains the interacting face (slave face), a face with which it interacts (master face), and the data describing the interaction (the contour of the face/face overlap is described by the number of edges, the edge nodes, the overlap centroid, and a set of edge flags).

Gap - The distance between a node and a face, in the direction normal to that face in most cases, defined as positive if the node is not penetrating the face and zero or negative if the node is on or inside (penetrating) the face.

NODE - A traditional node with position and no other attributes.

Node_Block - A collection of nodes of the same type. Currently, all node blocks must be of type NODE. All nodes that are connected to faces must be in the first Node_Block. Nodes that are not connected to faces (i.e., SPH particles, Gauss points, etc.) must be placed in Node_Blocks 2 through N.

NodeFace_Interaction - A set of data returned by ACME to the host code that contains the interacting node, the face with which it interacts, and data describing the interaction (contact point in local coordinates, Normal_Gap, unit pushback vector, unit surface normal, and algorithm used).

NodeSurface_Interaction - A set of data returned by ACME to the host code that contains the interacting node, the Analytic_Surface with which it interacts, and additional data describing the interaction (contact point in global coordinates, Normal_Gap, and unit surface normal).

QUADFACEL4 - A 4-node quadrilateral face with linear interpolation.

QUADFACEQ8 - An 8-node quadrilateral face with quadratic interpolation.

Search_Data - An array containing user-specified parameters (currently three: Interaction_Status, Search_Normal_Tolerance and Search_Tangential_Tolerance) that must be set by the host code to control the search algorithms for all possible pairs of interacting topological entities.

Search_Normal_Tolerance - An absolute distance defined by the user to determine, in conjunction with any physical motion, whether two topological entities interact. This tolerance acts normal to the face.

Search_Tangential_Tolerance -An absolute distance defined by the user to determine, in conjunction with any physical motion, whether two topological entities interact. This tolerance acts tangential to the face.

Static 1-Configuration Search - The search algorithm that uses only one configuration to determine interactions using a closest point projection.

Static 2-Configuration Search - The search algorithm that uses two configurations, current and predicted, to determine interactions using a closest point projection.

TRIFACEL3 - A 3-node triangular face with linear interpolation.

TRIFACEQ6 - A 6-node triangular face with quadratic interpolation.

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