AUTOMATED 4 AXIS ADAPTIVE SCANNING WITH THE DIGIBOTICS LASER DIGITIZER

INTRODUCTION

The DIGIBOT 3D Laser Digitizer is a high performance 3D input device which combines laser ranging technology, personal computing, and Microsoft Windows in an attractive desktop package.

With its full four-axis scanning capabilities, the DIGIBOT provides a simple, accurate, and quick way to copy or inspect complex, sculpted surfaces. The DIGIBOT provides an effective solution for many industrial and academic problems involving 3D design, inspection, replication, analysis, and visualization/animation. By measuring sequential points and producing a standard list of x/y/z coordinates, the DIGIBOT interfaces to any CAD/CAM/CAE imaging or animation software that reads 3D points, contours, or triangular facets.

UNIQUE BENEFITS OF THE DIGIBOT SYSTEM

The following unique benefits are provided by the DIGIBOT technology:

- DIGIBOT's ranging system measures individual surface points without using complex, non-linear imaging optics or sophisticated detector-array processing techniques.
- The ranging system provides high resolution and accuracy while maintaining a small, fixed triangulation angle across a large work volume.
- Unlike camera-based ranging devices, the Digibot Ranging System has a very long ranging length with a small stand-off and does not suffer from focal problems such as lens aberrations and depth-of-field issues.
- Systems can be mechanically configured to provide up to two rotations and two translations between the object and the ranging system.
- Advanced positioning capabilities make possible the complete, one-scan measurement of complex objects.
- Adaptive 4 axis scanning procedures minimize shadowing effects, provide optimal measurement orientations, and produce homogenous point spacing with no measurement redundancy.
- Semi-adaptive, systematic, and interactive scanning procedures provide efficient alternatives for less sculpted, more regular surfaces. A complete library of C-based system functions can be used to develop custom scanning procedures.
- The system is a peripheral device which interfaces to an IBM compatible PC through a controller board located inside the PC. The system is self-orienting and maintenance free. The Digibot calibration/registration procedure is quick and easy to perform. This procedure is much less complicated than the calibration/registration processes used for camera-based systems.

- DIGIBOT systems are easy to set up and move because of their small size and low weight.
- Digibot's windows-based software provides a conventional, intuitive interface to the scanning procedures and a variety of data processing utilities, including contour editing, surface editing, polygonal surface generation, adaptive surface filtering, 3D viewing, and data formatting.

DIGITIZING DESCRIPTION

Digitizing an object begins by first mounting the object on the platter in front of the laser scanning system. The operator then uses the Windows interface to select from a variety of scanning procedures, each of which will be more or less appropriate for a given object. Once selected, the operator instructs the system to execute the scanning procedure. Typical scanning procedures, systematic or adaptive, provide sampling rates on the order of 10,000-100,000 points per hour. A course sampling grid can be executed in minutes while high resolution sampling of complex surfaces can take hours.

DATA (GEOMETRY AND TOPOLOGY)

The DIGIBOT device, including the control software resident on the customer's host computer (IBM PC), is essentially an automatic data acquisition system. Typically, the next step after acquiring data with the digitizer is to manipulate the data for some purpose such as graphical display or numerical analysis. At this time the user must understand and appreciate the 'art and science' of using a set of discrete surface points to mathematically represent a surface. In essence, the 3D coordinate values of individual surface points only provide information about the geometry of a surface. A complete surface representation also requires topology (i.e. information about how each point is connected to its neighboring points). The selection of one scanning procedure over another will typically have a great influence on the amount of explicit topology information that can be acquired during the digitizing process. Some scanning procedures can provide complete topology while others provide only partial or no topology. Any data that is lacking in topology information must typically be subjected to some form of mathematical topology generator. A procedure of this type must attempt to establish topology from the available geometry. In general, the user must be aware that the selection of one scanning procedure over another also involves a conscious decision to use one data processing procedure over another.

ADAPTIVE SCANNING AND FILTERING

When measuring an analog subject, it is generally a good idea to perform a high resolution sampling procedure so that high frequency components are adequately resolved. This principle is appropriately applied when digitizing a 3-dimensional object. The representation of a sharp edge will typically require a dense grid of closely spaced surface points. Although essential, high resolution scanning procedures also present a problem. Slowly curving surfaces, which can be represented with relatively few widely spaced surface points, tend to be over-sampled producing excessive amounts of unnecessary data. The solution to this problem is provided by introducing some form of filtering mechanism which uses the local rate of surface curvature to adaptively adjust the spacing between neighboring surface points. With the DIGIBOT system, a filtering procedure of this type can be introduced in two ways. When digitizing, an adaptive scanning procedure can be executed so that the spacing between consecutive measurements is decreased for increasing rates of surface curvature. After digitizing, the acquired data can be subjected to a flexible filtering procedure which removes unnecessary points in over-sampled surface regions. Generally, the second approach is the most attractive and flexible (i.e. it is the best to over-sample the object and then use a data filter to selectively remove a desired set of surface points).

POINT MEASUREMENT BY TRIANGULATION

Individual range measurements are obtained using an active triangulation method. The ranging system is composed of a laser source and a translating photo-direction detector. The laser source and the photo-direction detector are positioned at two corners of a right triangle formed by the orthogonal intersection of the laser line and the base line. At the third corner of the triangular system the laser beam illuminates a small surface producing a diffuse point-source of light. The photo-detector is translated until the illuminated surface point enters the detector's field of view. At this time the system can accurately determine the distance and the angle theta from which the range can be computed.

Active triangulation requires that the surface be a relatively diffuse reflector and that the angle of incidence between the laser line and the surface normal be within limits. Polished surfaces cannot be measured because, in most orientations, no light will be reflected back toward the photo-detector. Increasing incident angles will tend to illuminate an increasingly larger surface area while decreasing the amount of light reflected back toward the photo-sensor.

There is a limit to the effectiveness of a triangulating range system. As surface concavity increases, the photo-detector's view of points located within concave regions becomes increasingly obstructed, producing increasing limited laser/photo-sensor orientations. Reduced probing angles provide improved probability but tend to decrease measurement resolution and accuracy. Typical applications will use a 30 degree probing angle.

RELATIVE MOTIONS (DOFs) BETWEEN LASER BEAM AND OBJECT

Assuming that the ranging device has a long ranging length and does not need to move toward or away from an object, there remains four forms of relative motion between an object and a laser beam needed to illuminate a point on any exposed surface of a 3-dimensional object. More specifically, a 3D digitizer needs two translational and two rotational degrees-of-freedom (DOFs) between the ranging system and object to provide full 3D sampling capabilities. DIGIBOT offers two translational DOFs and one rotational DOF. This is also known as four axis scanning. The laser can be translated vertically and horizontally while the object can be rotated about a vertical axis. By not providing the fourth DOF (i.e. rotation of the object about a horizontal axis), DIGIBOT is not capable of measuring points along vertical facing surfaces. For most applications, the practicality of using a 4-DOF digitizer is questionable due to mechanical, operational, and data processing difficulties. The fourth DOF can, however, be partially realized by digitizing the same object multiple times in different orientations. This approach requires that the multiple data sets be merged to form a single surface mesh.

By using different combinations of its three DOFs, DIGIBOT is capable of performing three types of 3D scanning procedures:

1. two DOF scan using two translational DOFs,
2. two DOF scan using translational DOF and rotational DOF, and
3. three DOF scan using two translational DOFs and one rotational DOF.

Each of these three scanning options is useful for different types of objects. Flat objects are best digitized using two translational DOFs while convex objects are best digitized using both translation and rotation. Three DOF scanning offers a very attractive method for digitizing complex objects with non-axial geometry, multiple contours, and concavities. The following three discussions provide a more detailed description of when and how the different scanning options can be used to digitize different types of objects.

SCANNING WITH TWO TRANSLATIONAL DOFs

Probably the simplest scanning procedure that can be performed with DIGIBOT employs two translations of the ranging system. As a result, this type of scanning option should be used to measure relatively flat surfaces. Once the user has decided which combination of motions are appropriate for a given application, a decision must be made to perform either a systematic scanning procedure or an adaptive scanning procedure.

The surface mesh generated from adaptive data is very attractive because it produces a homogeneous, evenly spaced set of points on all exposed regions of a surface. An adaptive mesh can also be optimized to provide more points in high frequency regions and fewer points in regions where high sample density is unnecessary. Though the data produced by adaptive scanning procedures is attractive, in practice it is generally more practical for simple-shaped objects to employ fully systematic procedures with only two DOFs. The reasoning for this is two fold:

1. the grid topology of systematic data is provided implicitly while the mesh topology of adaptive data must, by some method, be explicitly specified and recorded (this can be difficult), and
2. systematic data from a high density grid can be adaptively filtered to produce an adaptive surface mesh that is very similar in quality to that produced by adaptive scanning procedures.

Though adaptive scanning methods are used for most applications, systematic scanning procedures should be used whenever possible because they are easy to perform and they provide structured data that can be flexibly filtered to provide an optimal data sub-set. Another advantage to using high frequency systematic sampling procedures is realized when the user decides that more data is needed. It is generally easier to refilter a set of data than to re digitize an object.

SCANNING WITH ONE TRANSLATIONAL DOF AND ONE ROTATIONAL DOF

A very popular form of 2-DOF scanning utilizes both rotation and translation. By first positioning the laser line to pass orthogonal through the center of rotation, a set of radial measurements can be obtained by rotating the object and vertically translating the ranging system. This scanning configuration is useful for convex objects because acceptable incident angles are possible only at locations where the surface normal does not depart significantly from the radial direction. When choosing between systematic versus adaptive scanning procedures, the very same reasoning, introduced in the previous discussion describing 2-translation scanning, can again be used. A systematic scanning procedure will produce a data-grid (with complete topology and filtering capabilities) by incrementally rotating the object and incrementally translating the ranging system. Some subtle properties of rotation contour sampling are:

- points with a surface tangent that passes through, or near, the center of rotation cannot be measured,
- negative radiuses can be measured because the active range of the ranging system extends past the center of rotation,
- closer spacing between measurements occurs along contours that are closer to the center of rotation,
- off-center objects are sampled during two portions of a complete rotation causing partial loss of topology and partial loss of the contour on two sides where large incident angles make measurement impossible, and
- most concave surfaces cannot, or can only partially, be measured.

Two DOF scanning procedures are very attractive because they are easy to perform and they produce data that is easy to work with. Unfortunately, the type of object that can be digitized using 2-DOF methods is limited. With its third DOF, DIGIBOT is capable of digitizing much more complex objects, including off-center contours, multiple contours, and concavities. However, as a general rule, 2-DOF scanning procedures should be used whenever possible to take advantage of gridded data and to avoid the difficulties associated with the processing and compatibility of 3-DOF data. The reasoning behind this rule will become clearer after reading the following description of 3-DOF scanning.

SCANNING WITH ALL THREE DOFs (4 AXIS SCANNING)

The work volume generated using all three DOFs (i.e. rotation of the object and both vertical and horizontal translation of the laser line) will be cylindrical in shape. With three DOFs, DIGIBOT provides a work volume with an 18" diameter and a 18" height. The advantage of using a third DOF is two fold:

1. the surface normal at any given point is limited only by the requirement that it not depart significantly from the horizontal, and
2. each individual point can be measured from a variety of different perspectives (i.e. the laser beam can illuminate a single surface point from a variety of different directions).

Complex contours can be better sampled along a horizontal plane by both rotating the object and translating the ranging system. Deep concavities and multiple contours can only be measured using both rotation and translation while, for complex contours of this type, rotations by itself will yield comparatively poor results.

An efficient 3-DOF procedure for sampling contours along a horizontal cross-section requires adaptive feedback control. The direction and rate of curvature along a contour are computed using previously acquired points to help predict the location and surface normal of a target point (i.e. the next point to be measured). In this way, the object is rotated and the ranging system is translated to provide an optimal measurement perspective (i.e., the laser as normal as possible to the surface) for each consecutive target point as the system adaptively tracks a contour. For convex surfaces, the optimal measurement perspective is obtained with a zero incident angle between the laser beam and the surface normal. For concave surfaces, optimal measurement perspectives are obtained when the laser line is closely pivoted about the outer edges of the concavity. Orientations of this type will typically produce non-zero incident angles. A very useful result of adaptively moving along a contour can be seen by measuring consecutive points. The system effectively acquires complete topology information (i.e. the points are connected in the same order in which they are acquired) and, when multiple contours exist, each contour is scanned separately (i.e. once started, the systems attempts to complete a contour by pivoting around any other obstructing contours.)

Though two DOFs are used to scan adaptively within a horizontal plane, the third DOF is typically used to systematically position the ranging system at vertically displaced planes. For this reason, this type of 3-DOF scanning could be referred to as 'semi-adaptive.' It is important to recognize that adaptive scanning along planar cross-sections provides complete contour topology in the horizontal direction. This is a great advantage but, by blindly moving to vertically displaced planes, semi-adaptive scanning will provide no vertical topology between neighboring cross-sections (i.e. no information is provided to establish how points in one planar contour are connected to points in a corresponding, vertical-displaced planar contour). As a result, a procedure for vertical topology generation must be employed before a valid surface mesh can be obtained from semi-adaptive data.

A filtering mechanism can be incorporated into the procedure for semi-adaptive scanning to provide a flexible way to discriminate between rapid and slow rates of surface curvature. By using the local rate of surface curvature to adjust the spacing between consecutive measurements, a relatively small number of measurements are needed to define a contour containing sharp corners and slow curving sides. Without a filtering mechanism, a contour of this type must be sampled frequently to guarantee that the sharp corners will be adequately resolved. Such a procedure will require significantly more time and will, in this case, produce an over-abundant amount of data along slow curving surfaces.

There is, unfortunately, a competing disadvantage to using an adaptive filtering mechanism along planar cross-sections when performing a semi-adaptive scanning procedure. By systematically stepping to consecutive planes, no filtering mechanism is applied in the vertical direction producing a non-homogenous surface mesh composed of long, skinny polygons. This problem can be resolved by employing a vertical filter either during or after the scanning procedure. When scanning, a fully adaptive procedure is fast and concise but it is difficult to implement and the resulting data must explicitly specify topology. After scanning, a vertical data filter must first be applied to produce a homogenous surface mesh which will also require explicit topology information. As a consequence, unless time is a factor, or for some other specific reason, it is generally more practical to execute a semi-adaptive scanning procedure with equal sample spacing in both the vertical direction and along horizontal contours. The data produced from such a procedure can be subjected to a vertical topology generator, and then filtered to extract the desired data subset.

SUMMARY

The Digibot 3D Laser Digitizer is a high performance 3D input device which combines laser ranging technology, personal computing, and Microsoft Windows in a desktop package. With its full four-axis scanning capabilities, the Digibot provides a simple, accurate, and quick way to copy or inspect complex, sculpted surfaces. The Digibot provides an effective solution for many industrial and academic problems involving 3D design, inspection, replication, analysis, and visualization/animation. By measuring sequential points and producing a standard list of x/y/z coordinates, the Digibot interfaces to any CAD/CAM/CAE imaging or animation software that reads 3D points, contours, or triangular facets.

The DIGIBOT uses a unique triangulation technique that does not use complicated imaging optics or array detectors. The scan head resides outside of the scan region and does not move back and forth from the object to maintain focus of the laser beam spot. Consequently, scanning is simple and efficient. Adaptive scanning procedures intelligently position the beam spot on the object's surface while effectively walking from one point to the next. For complex objects, this technique, unique to the DIGIBOT, can reach into deep concavities, undercuts, and between surfaces to produce a complete, homogeneous data mesh. Simple systematic scanning procedures produce grid data for single faced (i.e., flat-faced) objects or convex, cylindrical shaped objects.

Three dimensional modeling is becoming the technology of choice for the majority of designers and manufacturers. In order to be effective, many industries need to automate the acquisition of 3D geometry into the computer. The Digibot solves this need with industry leadership in technology, usability, and affordability.