Advances in the Field of Reverse Engineering

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ABSTRACT

This paper presents an overview of advances in the field of reverse engineering over the last 25 years. Initially, several basic definitions and terminology will be reviewed, followed by a discussion of how and why the foundational technology (both hardware and software) has developed. This will be examined from both a driving research and market demand perspective. The evolution of hardware, such as detectors, cameras, optics and sources will be discussed with particular emphasis on landmark developments that transformed the field. Significant advances in the methodologies and algorithms underlying software tools will also reviewed. A look at the latest developments and achievements in reverse engineering techniques shows the incorporation of knowledge based and CAD driven approaches. The paper will conclude with several state-of-the-art reverse engineering case studies from the fields of computer arts, medicine, dentistry, product development, manufacturing and virtual heritage. The authors consider the many possible future directions and applications of this field.

Keywords: reverse engineering, digitization, segmentation, surface reconstruction, geometric constraints

1. INTRODUCTION

As the applications for reverse engineering grow more widespread and diverse, it is worth outlining the technology and reviewing its development. A common interpretation of the phase "reverse engineering", first used in publications in the 1970s revolves around copying an original. Reverse engineering technology enables the creation of a digital model using data collected from an existing object. Research from areas such as image processing, computer graphics, advanced manufacturing and virtual reality has converged around creating a computer-based representation of the authentic article. In engineering applications, comprehensive reconstruction of the part form is required to recreate the original object while deviating from the measured points by less than a predefined tolerance. [11]

In a broader sense, an object may be given a virtual representation based on physical form and possibly the design intent of the original article. With this in mind, data capture need not be the starting point or automated modeling of surfaces the end goal, leaving the door open for more interactive, knowledge driven approaches. Potential information sources for reverse engineering projects can be physical parts, CAD file formats, milling g-code, laser scan data and CMM data. For several decades RE was incorporated into the manufacturing process and commonplace on the shop floor, in the following traditional production applications.

- First Article Inspection
- Tool and Die Verification and Repair
- Re-creation of CAD legacy data from master parts
- Generation of 'as built drawings' for part and systems

An article may exist in the absence of descriptive geometry because data was either not used for its creation or has since been lost. Engineers can use nondestructive probe techniques to extract the design concept and details stored within the finished part. Computer-aided-engineering analysis (CAE and FEA) has become routine in the design cycle and relies on 3D scan data to verify models created or changed by hand before a manufacturing run takes place. RE is also fruitful in the final stages of product development, when concerns turn to industrial design and packaging studies.

In the last decade, reverse engineering has been evolving along side the area of rapid prototyping. Research into the two technologies often intersected and their fundamental application theory has become interrelated. This paper will highlight how three-dimensional surface reconstruction may not be a necessary step in the RE process. Part data could be captured in a way that permits manufacturing, using a layering technique based on data from select 2D contours, which is the essential basis of most rapid prototyping techniques.

Reverse engineering shows promise in emerging applications such as mass production of customized devices and build-to-order manufacturing. In order to be successfully implemented in our global commercialized society, these areas will most likely require a high degree of automation; a persistent goal for RE technology. The market for the technology is diversifying, spanning automotive, aerospace, entertainment and consumer goods industries such as jewelry, clothing, sporting goods and recreation. In a world driven by demanding and impatient consumers, another application where reverse engineering proves particularly appropriate is competitive analysis.

The ideal approach to an RE challenge is swift and intuitive. A traditional reverse engineering process is carried out in three main stages

- Capturing the part data
- Reconstructing the surfaces
- Creating a usable and useful model of the part

The terminology that describes the process from start to finish will be defined in section 2. The data capture should be fairly hands free, accomplished with little intervention, yet the parameterization and surface creation phase needs considerable influence over the result, likely requiring in progress input and manipulation of the components. The created surfaces should be constructed consistent with the future purpose of the model and be accurate within a tolerance defined by the intended application. The latest approaches for generating the optimal RE model and optimizing the downstream uses of the model are discussed in Section 4. Section 5 takes a look at interesting and state of the art applications of RE technology. The paper wraps up with Section 6 entitled, 'Future Directions of Reverse Engineering'.

2. TERMINOLGY

The terms in this section are defined in order as they occur in the standard implementation of a reverse engineering solution, although the stages are often iterative and overlapping. [13] ***Data capture*** is the process of collecting XYZ points in space to represent an existing physical object. The resulting point cloud, a collection of data stored as an array of discrete co-ordinates, now defines the object's shape and dimensions. At this stage, a preliminary computer graphical description of the object is possible. ***Digitization***, the physical procedure of acquiring numerous coordinates from part surfaces can be either manual or automated, using a range of hardware. A range image is a map of depth information at different points on a scene. The (x,y,z) triplets can be unstructured or structured (for example, organized to lie in parallel planes).

Point clouds can be captured from many viewpoints, to fully describe the entire geometry and cover any occlusions (blind spots or omissions) that result from overlapping or recessed features. ***Registration*** is necessary to combine these multiple sets of data, and align them to a global co-ordinate system. Carefully merging overlapping views or uniting unconnected views based on information about the transformations between the viewpoints accomplishes this step. Since points are usually sampled at a much higher density than necessary, a ***data thinning*** method is introduced to select a random sampling or structured subset of the points. For computing a base surface that follows simple data, 10% of the original points may be all that is necessary for inclusion in the parameterization process [11]. The post-processing step may also attempt to remove outliers (clean-up).

Triangulation gives a discreet representation of an object via a set of polygons that defines the whole without deviating from the collected points by more than a given tolerance. For visual and future computational purposes, this wireframe mesh approximates the shape and size of an object using triangles. Smaller triangles result in a better approximation, inevitably at the expense of file size and processing speed. This stage is sometimes referred to as meshing the convex–hull, as a covering of connected vertices now bounds the empty 3-D interior region in space. Algorithms like Delaunay triangulation, which inscribes a circle until no more vertices fall within, determine a suitable number of triangles to fit an area of changing topography. The term ***tessellation*** may be used to describe the resulting model, which is the end of the line for some applications (for example, computer rendering and animations).

Boundary representation algorithms are formulated to efficiently segment point data into regions, detecting profiles for linear extrusions and surfaces of revolution. The end goal is to describe the complete topology of an object bounded by simple analytical surfaces or swept features fused by blends, namely a ***B-rep model***. [1]

Automatic ***segmentation*** divides 3-dimensional digitized data into surface areas or zones. Segmentation can be achieved using a combination of region growing and edge based approaches. Many engineering assemblies and their component parts are comprised entirely of planar surfaces and simple analytical shapes. The faces are typically separated by sharp edges, characterized by abrupt changes in the direction of the normal vector of adjacent mesh elements. An edge detection technique based on the computation of normal vector angle changes beyond a certain allowance delineates mesh region boundaries. Surface reconstruction can be accomplished easily by fitting surfaces individually to each given region, thus making segmentation a critical step at the outset of the surface reconstruction stage.

Parts with smooth curvature change properties gradually and are more suited to a face-based approach to edge detection by employing the concept of ***region growing***. One starts with a seed region and determines the geometric parameters for modeling the data of the region. The seed region expands as long as the parameters of the model do not vary too much. This technique aggregates meshes into a region until the area of aggregated meshes reaches an area threshold from a series of seed meshes. [8]

Surface reconstruction happens concurrently or subsequently as surfaces are fit to the divided regions of data. The type of surface depends on the form of the part; complicated composite of simple geometric features or bounded mound of flowing unstructured contours. For the latter, fitting the data with low order parametric surfaces, such as NURBS (non-rational uniform B-spline) surfaces is a good choice to define a 'skin' of mathematical patches. For conventional engineering objects, planar surfaces and quadrics can be attached to the ordered points. Free-form surfaces may be reconstructed simultaneously by updating neural networks that correspond to the separate patches. [6]

Constrained fitting takes place as the surfaces are selected and applied, guided by regularly occurring geometric relationships between faces and features. As the basis for fitting a surface to the measured points, prioritized geometric constraints form a set of sequentially solved sub-problems that are resolved in a consistent way and imposed on the model. [3]

Model ***beautification*** is the final step wherein a b-rep model, with incoherent topology present along model edges and at the intersecting vertices, is improved by resolving gaps, removing sliver faces and eliminating negligible edge segments. [7] The process undertaken to identify aesthetic and functional dissimilarities between original mock-up or real artifact and the resulting model, is know as model ***validation***.

3. TECHNOLOGY DEVELOPMENT

This section discusses how and why the foundational hardware and software technology has developed. Research during the last two decades has taken a practical and field oriented focus, requiring once cumbersome and extremely costly systems to be available as portable, flexible units. Enhanced products recently available on the 3D scanner & digitizer market have meant higher performance at a lower cost, without sacrificing accuracy and efficiency. Another breakthrough since the days of mainframes came about with the rise of powerful desktop computing hardware that can cope with and easily process super large data sets. Several notable and well-used products have been identified out of a vast array of software options. However, too many hardware devices are bundled with equipment specific packages developed by / for the manufacturer, inhibiting the emergence of industry standard software choices as clear leaders.

3.1 Evolution of the Hardware

Data collection is broadly grouped into two classifications, contact and non-contact methods. Part digitization accomplished using tactile devices allows higher accuracy yet is much slower, potentially damaging to the part and definitely only suited to rigid objects. Optical, acoustic and magnetic non-contact devices have noise, or systemic error as their main disadvantage. There are a number of physical factors that can affect the quality of the digitization:

- Overall dimensions
- Shape of the inside and outside corners and edges
- Existence of holes and concavities
- Color and surface finish of the object
- Inorganic, lifeless object vs. organic, animate object

Technical considerations include the digitizer's motion system, work volume, speed, and resolution, the positioning and/or mounting of the object being digitized and vibration or noise in the system. Although even dispersion of the data points is desirable, arbitrarily scattered points are typically the end result of the digitization phase.

3.1.1 Non Contact devices (Optics, Laser Scanners)

Non-contact digitizers use lasers, moire interferometry, and patterned light techniques. Laser scanners illuminate either a small spot or a thin line of light on the surface of an object. Systems that project a line are hundreds of times faster at collecting point data than those illuminating a spot of light. Since planar scanners cover area faster than point scanners, they are useful for reverse engineering tasks involving large objects. Both use a technique known as optical triangulation to determine the location of points in 3D space. A directed laser beam is set-up at a baseline distance from a digital camera, oriented at a known angle with respect to the beam. The pupil of the camera collects light scattered back by the object. From the position of the light point as seen by the sensor it is possible to calculate the range and angle between the laser and the illuminated point of the object. In an established coordinate system, the (x,y,z) coordinates of the point can be obtained by these range measurements.

Using a charged coupled device (CCD) array, the received reflected laser light indicates the center of the spot using a form of triangulation. Coordinates that lie directly on the surface of the digitized object are calculated and recorded as the scan proceeds over the object according to the operator's programming. There are optical tradeoffs between depth of field versus accuracy and range.

Laser digitizing ensures complete coverage of a part and enables digitization of the most intricate detail. The laser scanning process captures sweeping curves and lofted surfaces that are difficult to measure using more traditional measurement technologies. Accuracy of these devices can be up to 0.1mm. Laser digitizing is not without its limitations. Because the process is based on analyzing reflected light, it is susceptible to misinterpreting light reflected from certain surface types. Objects that are shiny or brightly colored have a tendency to distort reflected laser light in the eyes of the CCD array. Similarly, transparent and translucent objects may reflect some of the light from within them, corrupting the surface coordinates. The triangulation technology has difficulty picking up light reflected from a right angle, although multi-axis scanning mitigates this problem. Laser digitizing works best with white or light gray objects with a flat matte finish. As long as doing so would not harm the object, as it would in the case of artwork or valuable artifacts, paint or powder can be applied to the object to overcome the aforementioned problems. For objects beyond the 0.2m – 2m range, a time-of-flight range measurement approach may be better suited. A laser or light beam emitting device is still used but the co-ordinate location of the reflected light is calculated, by its path of travel in combination with the time for the return trip from source to sensor. Medical and industrial scans, such as MRI (magnetic resonance imaging) and CT (computer tomography) are non-contact approaches that obtain dimensional data from the interior of an object.

3.1.2 Contact Devices (Sources, Digitizers, Stylus)

Most contact digitizers are manually operated using a hand guided probe, or stylus, although certain coordinate measuring machines (CMMs) travel a path controlled by numeric code. In the general case, data is collected one point at a time. Some systems permit the user to collect a string of points by dragging the tip of the probe across the object's surface. Co-ordinates are registered when the tip crossed a pre-defined collection plane. Creating a polygonal mesh using a probe-based digitizing system is slow and tedious. But probe systems have the advantage of being easy to control and set limits on the information obtained. If you need only a few curves, or need to inspect the location of a few points on a surface, a probe approach is recommended.

The major manufacturers of digitizing robots and arms have been consistently supplying hardware to production floors and quality control or metrology labs for several decades. These include Faro, Immersion and Roland for mechanical touch probes devices and laser scanners from among others Minolta, Romer, Mitutoyo, Polhemus and Cyberware.

Under the heading of emergent techniques, haptic devices are explored as a means to create a virtual model from a physical form. The haptic device is the central mechanism for constructing a three-dimensional part with force feed back making the process more intuitive. This section concludes with the notion that compared to the accuracy capacity of data acquisition hardware, relatively far more error will be introduced during the downstream conversion process from raw data into a usable 3D model.

3.2 Commercial Software Packages

For industrial and commercial projects, an automated transformation process of a real object to a three-dimensional (3D) surface representation or solid model is sought. Various commercial CAD-related products provide specific capabilities for supporting traditional RE. The working file formats of CAD are DXF, STEP, IGES, STL and others. Dedicated reverse engineering software can be purchased as an independent offering, whose output is compatible with generic CAD packages. Alternatively an 'add-on' component may be available to complement the main CAD platform in doing specific RE tasks. These products are designed to aid in creating digital models from physical originals by converting point clouds from scans to polygons, and furthermore from polygons to NURBS. Special purpose reverse engineering programs may have many tools for performing general 3D shape manipulation, but their main focus is on the process of converting raw point data from the input devices into a more usable polygon or NURB surface representation with the least loss of accuracy. The intention is to enhance the designer's capability to incorporate physical models into a digital design workflow. Often one module or product is employed to mesh the cloud data, while another converts polygonal meshes to a NURBS surface model.

Success in harnessing research through the commercial market has been achieved by two notable contenders in the field. Paraform and Raindrop's Geomagic Studio are both leading reverse engineering software products, whose development was assisted by significant contributions from respected published researchers.

Alias|Wavefront has enhanced the reverse modeling capabilities of its Studio Tools suite of computer-aided design products with a module named, Spider, which compares to a certain extent with leading reverse engineering products such as Geomagic and PolyWorks from InnovMetric (Montreal, Canada). Rhino is another product that combines

NURBS surfaces and modeling. INUS Technology offers a similar feature workbench with leading RapidForm 3D scan processing software.

Reverse Engineering 2 (RE2) from Dasault is specifically configured to work with CATIA. RE2 offers a powerful 3D tessellation system particularly adapted to mesh huge point clouds (up to several million) for mechanical parts. A powerful complimentary tool, Quick Surface Reconstruction 2 (QSR2), allows quick and easy recovery of surfaces from digitized data and offers several approaches depending on the type of shape: free form fitting, mechanical shape identification (plane, cylinder, sphere, cone) and primary surface extension. The tool analyses curvature or iso-slope properties, so users can easily create polygon segmentation in pertinent surfaces areas. QSR2 includes its own quality checking tools. CopyCAD is a package from the DelCam Company aimed at producing smooth CAD surfaces from digitized data, for use in a range of product development applications. It facilitates the process of generating surfaces with a high degree of curvature.

Revware, formerly Design Automation, offers Rev Works, a feature based digitizing add-on for use with partner CAD package SolidWorks. This product is essentially a functional tool bar with basic calibration and data capture functions; feature measurement, draft angles, lengths, depths, radii and face angles.

All of the products have common functionality; addressing digitalized data import, clean up, tessellation, cross sectioning, shape contouring and quality checking with real time resulting diagnosis. Software packages have automatic compensation for geometry for probe tip radius in concert with the hardware devices. For optimal quality and faithful polygons, software should automatically thin the data and reorganize the mesh edges, thus reduce the computation time to realistic levels. Not all packages do this step, resulting in inefficient processing of a huge mass of unstructured points. An important step is to ultimately transform the desired shape, a polygon set, into a CAD surface.

"Over the last couple years, we've seen somewhat of a turning point for reverse engineering," says CAD Market Researcher Terry Wohlers, of Wohlers Associates, Inc., Fort Collins, CO. "We're now seeing software that dramatically helps to bridge that gap between going from a laser scan to inputting the data into a CAD program."

Fringe products, such as face customizing software, are of interest to the film, gaming and even beauty industries. These specialized packages do not have an engineering focus but use the core imaging and surfacing technology that RE is based on. One or more photographs are used to generate unique human face models that can be modified, made over or animated through surface manipulation or special effects.

3.3 Underlying Algorithms

Significant advances in the methodologies and algorithms underlying reverse engineering and surfacing software tools have been reviewed. Acquired data is used to create surfaces that are recognized by industry standard design (CAD) packages, such as Pro/Engineer, Catia, SolidWorks and manufacturing (CAM) programs like MasterCAM. These surfaces can be further re-created in a fully parametric format. Three main focus area for mathematical algorithms are identified as

- Segmentation and edge detection
- Surface reconstruction and Parameterization
- Constraint Fitting.

4. CHALLENGES AND ACHIEVEMENTS

Emerging reverse engineering research is classified in this section with a highlight on several distinct approaches.

4.1 CAD Driven Approach

The now de facto CAD approach of the modern part designer is to build a parametric solid model. Think of CAD driven RE as model formation with in-progress user controlled data capture process. Instead of reconstructing a surface model of an engineering object, with clearly identified extruded and revolved features, a solid model is constructed from the ground up. Because all the numeric and geometric information input in the modeling process is collected a priori from the physical model, the procedure is classified as user guided. [3] The sketch profiles required for base extrusions or surfaces of revolution are tackled first. This may require setting up datum planes and collecting a ray of data across the part surface on the base or mid plane. A long list of detail features such as holes, chamfers, fillets, slots, pockets and draft angles can be applied to the base model in a logical sequence. For traditional mechanical assembly parts, consisting of planar or primitive surfaces with a multitude of symmetrical and arrayed features, the technique is efficient and only the measurement mechanism limits the accuracy. The measuring device would typically be a digitizing arm with 3 or more degree of rotational freedom.

4.2 Adaptive Slicing of a Layer Based Model

A surface model is typically reconstructed from a large arbitrarily scattered point cloud and then converted to a STL file format. If the part is to be fabricated by rapid prototyping, the STL file is sliced to generate a series of layers. The shape error of the final RP model comes from three sources, which will make it difficult to control the shape of the error of the RP model. By far the fastest route is to go directly from point cloud to a RP slice file (layer-based model). Therefore there is basically only one source of shape error. The cloud data is segmented into a number of layers by slicing the point cloud along a user-specified direction, also the RP building direction. The mid-plane in the initial layer is used as the projection plane and the points within the layer are used to reconstruct a closed polygon approximating the profile curve. Two slicing approaches for determining the layer thickness, i.e. uniform slicing (at equal intervals) and adaptive slicing. If the layer thickness is sufficiently small, a smooth part model can be obtained. This may, however, result in many redundant layers and a long build time on the RP machine. If the layer thickness is too large, the build time is short but the part may have a large shape error. For implementation of the iterative procedure, a binary search algorithm is developed for finding the thickness of a given layer. Lastly, the RP layer contours are faired and subsequently closed to generate the final RP model. [14]

4.3 A Destructive Technique

Reverse engineering and rapid prototyping (RP) are far from being competing technologies. Rapid prototyping and laser digitizing can be integrated into the same design cycle for many projects. A developing sub process of RE is Capture Geometry Inside (CGI). It is a destructive technique that amounts to RP in reverse. The main advantage of CGI is the ability to digitize internal features that are otherwise hidden with standard scan hardware. Before digitizing the original part, it must be cast in a liquid polymer that solidifies. The block is face machined by CNC mill to expose a series of layered contours. A 3D representation is complied from the parallel scan images. Then surface-modeling software can be used generate a database for engineering analysis, rapid prototyping or design modification.

5. INTERESTING APPLICATIONS

5.1 Computer Arts

Computer animation and rendering are increasingly prevalent in the film and video gaming industry. A large number of computer programmers and specialists are employed in the video game arena, where mega projects like Xbox from Microsoft Corporation and Playstation from Sony are generating huge revenues for technology companies, on both the software and hardware sides. Reverse engineering is used to create realistic digital representations of props or figures that will be transformed and realized on screen. Occasionally the major artistic inspiration for the feature characters in a game or movie comes from a sculpted model or hand crafted figurine. The “one of a kind” piece is scanned and the point cloud translated into a workable data set. Individual humans, as opposed to manikins can also be scanned to ensure proportion and facial resemblance.

How about statues of ancient Roman gods for state of the art? The IMAX statues that stand in front of Caesar’s Palace in Las Vegas were realized using HighRes reverse engineering software. The makers of the film trilogy Lord of the Rings used 3D scans of full-scale clay maquettes to animate many of the feature creatures. Weta Digital, the in-house special effects group, teamed up with Applied Research Associates, the company that developed hand held FASTscan equipment, now sold by Polhemus. Those in charge of the project were impressed with the flexibility of the scanner wand to intricately capture every inch of the model from any angle. Several passes over the model surface were stitched together using proprietary scanner software. Using Alias|Wavefront's PowerAnimator software, dense point cloud data collected from the 10ft cave troll maquete was converted to a high resolution NURBS surface model with 3.7 million control points on 250 surface patches. Because the high resolution model was to unwieldy for computational purposes the modelers embarked on creating a lower resolution surface, matched in shape and detail to the scan data and aligned to the former surface. Calculated height distances between the two surfaces formed the basis of a displacement map, to which an image of superficial /texture information was applied. Using the new model with only 28,000 control vertices, in combination with the displacement map, the model could be animated and rendered. The technique that was used, had it origins in the 1996 Siggraph paper "Fitting Smooth Surfaces to Dense Polygon Meshes" by Venkat Krishnamurthy and Marc Levoy. The resulting integral polygon mesh was extremely detailed and a faithful digital reproduction of the artist’s creation. [12]

5.2 Medical

Medical scan technology has an important place in the area of bone and tissue reconstruction. Implants and prostheses can be tailored to meet a patient’s exact requirements, helping a wide range of people, including victims of bone disease, cancer, congenital defects and traumatic injuries. The data from non intrusive scans, such as CT or MRI, is used to create a 3D model allowing technicians to perfect the shape, performance and integration of the implant into existing structures within the body. Several research organizations use RapidForm's 3D imaging technology to convert CT & MRI scans into CAD models for advanced neurosurgical and biomechanical research, and to build rapid prototype copies of the anatomy. Stereo-lithography takes these images and converts them to polymerized resin 3-D models allowing doctors to hold the information in their hands and examine all of the data at once. A more complicated approach is to fit a mathematical surface of lofted polynomial curves to the cross sectional boundary data from the successive serial scans. The Bernstein basis function network is an example approach to performing the functional approximation task necessary for reverse engineering bone structures, with the end goal of producing a customized implant. [6]

The COMPRU head and neck reconstruction unit at Misericordia Hospital in Edmonton, Canada has dramatically enhanced the process for making facial prosthetics. Rather than spending tedious hours hand sculpting, the advanced facility is using Roland 3D scanning and milling devices to produce prosthetics that both look more realistic and increase the time spent with patients. "It saves a significant amount of time over hand sculpting so that I can quickly establish form and position. I can focus on the final details that make the prosthesis realistic" claims the anaplastologist. The final result is realistic and well proportioned, often making use of mirrored data from unaffected areas on the opposite side of the patient's body to ensure symmetry and likeness (for example, with an ear prosthesis).

Interestingly, engineers have developed the first interactive computational toolkit to reverse engineer a living thing. The aim of this research is for anatomists to better understand the relationship between form, function and behaviour by recreating the biomechanical capabilities and limitations of muscle, ligaments and bones. The product called Vertebrate Analyzer holds significant potential for medical and dental applications. Its main focus is creating mechanically articulate and animate skeletal models.

5.3 Dental

If there is one field where this niche technology should be exploited as much as possible, it is in dentistry and RE is already making headways. Some scanning software is dedicated specifically to making digital models of dental patient impressions. The hardware for these applications must also meet stringent requirements, such as a very high spatial resolution (better than 0.003"). This demands a tightly focused laser at close range (around 3"- 4"), yet having a field of view sufficient to image 3 teeth in a single scan.

A successful large scale operation to mass produce a customized device brings together the best of reverse engineering hardware and software. Case in point, the company, Align Technology of Califormia, manufactures clear, molded, removable thermoplastic shells called aligners to do the work of permanent metal braces. The process is based on a series of scans collected during the layer by layer destruction of the study model poured from an actual patient dental impression. Surface data from the scanning process is sent to a facility in Pakistan where it is analysed and processed by skilled computer technologist to create the sequence of progressive orthodontic arrangements that will achieve the end goal of straightening or repositioning the teeth. Raindrop's Geomagic software is again the product in use for this comprehensive step. The data comes back via internet and is sent to a stereolithography machine to produce all the models required for the complete set. Then a thermoformed shell is made for each step in the treatment and the set is shipped back to the local dentist. Patients wear the removable device for only two weeks before moving to the next. This reverse engineering technology not only allows custom manufacture of the aligners at various stages of treatment but makes a simulation of the orthodontic correction process possible, using the patients own data set. RE brings the cost benefit and time savings of mass production to a high priced application by permitting batch production with individual data files.

5.4 Design / Product Development

The reverse engineering process is a key step for manufacturing companies to create innovative products. After an industrial designer sculpts a clay model or creates a wooden mock-up, a 3D laser scanner is used to digitize the model into 3D point cloud data. In order to edit the file, it must be transformed into a polymesh file or NURBS based model with software tools. A functional prototype can be quickly produced in just a few hours, after generating accurate tool paths with CAM software. Digitization as a reverse engineering tool grew, in part, out of the requirements of manufacturers that rely heavily on physical models. [5] For example, one automotive company in Detroit used a laser digitizing system from Laser Design Inc. (Minneapolis, USA) to rework the form of a side-view mirror prototype. The problem was the mirror assembly produced severe vibrations. Designers experimented with various alternative contours in clay, subjecting each to wind tunnel testing. Eventually, a non-vibrating design was developed that met the functional and aesthetic requirements. No design documentation existed aside from the clay model. The laser digitizing system was used to extract CAD/CAM geometry directly from the ideal instance.

A sunglasses manufacturer used a destructive scanning technique to ensure part symmetry and generate the same design with specific size adjustments. Starting with a handcrafted original encased in epoxy, horizontal layers were sliced off and scanned at successive intervals. This method has obvious limitations with large or valuable or irreplaceable articles.

Designers and engineers can more readily collaborate on shaping a new concept. The key success factor is quick and faithful recreation of the physical conceptual mock-up, into a CAD model. The new digital mock-up becomes the reference archetype to be presented and discussed within the company and with clients. "One of the real advantages for us was having confidence in the overall modeling process," says Gasperi, the originator of Noveletti, a product design company. "It allowed [the artist] to focus on what he does best: express himself through creative approaches and design, rather than being forced to become an engineer in order to realize our vision."

At the beginning of the product life cycle, an industrial designer sculpts a clay toothbrush model for Johnson & Johnson Company. A 3D laser scanner is used to digitize the model into 3D point cloud data. In order to edit the object, it is converted into a NURBS based file with software tools such as Alias Spider. Then, Johnson & Johnson engineers quickly produce a functional prototype in just a few hours. After generating accurate tool paths with IDEAS CAM software, they simply set up the milling device with the called for tools and proceed with milling the injection molding dies.

5.5 Manufacturing / Product Validation

One goal of RE in the manufacturing sector is to generate a production and quality assurance database for an existing part. The process uses CAD models of the prototype in designing molds and in automated inspection of parts with complex surfaces (Auto, naval, aerospace etc). In many industries, such as aerospace and automotive, the ability to deliver high-quality, complex parts that meet stringent quality guidelines is a key business driver. With widespread use of 3D solid models that comprise precise engineered features, it has become increasingly important that, fast and accurate deviation results are obtained, via a robust QA/inspection process. Since the milling process may not always accurately replicate a computer model, one needs to know exactly where and by how much the end product deviates from the design. 3D scan data from production parts may be compared to their original CAD designs, ensuring that critical tolerances and quality standards are met. Paraform Inspection is a product designed for this market need that is easy-to-use, as well as fast and accurate. Traditionally, only CMM-type checking has been available, which compares only critical data points. The process is slow and does not give the whole picture. However, with the advent of high-speed scanning and inspection tools, the as-manufactured (point cloud) data can be compared to the as-designed (solid) data. This provides visualization of deviations, which can be used to make good/bad decisions or take corrective steps. Howmet, a division of Alcoa that manufactures aircraft jet engines compressor and turbine blades, implemented a first-article inspection process that combines a white-light scanner with computer-aided-inspection software from Raindrop Geomagic. The scanner digitizes the blade by projecting patterns of white-light onto the object's surface, while stereo cameras capture the patterns and calculate precise 3D coordinates of million points in just mere seconds. The complete 3D data set of the scanned blade is saved as an STL file and brought into Geomagic Qualify, where a critical object surface to original CAD model comparison is made.

5.6 Cultural Heritage

Virtual heritage is the term selected to describe capturing the shape of artifacts for archeological and historical purposes. Material articles generally deteriorate over time, especially if handled often, located in a polluted environment, exposed to light or subject to abuse. A specific artifact may represent the last of its kind and history has shown that unique and authentic pieces have not always been preserved for future generations to experience. Reverse engineering can readily be used to preserve inanimate objects of anthropological or cultural importance in virtual or replica form. A comprehensive three-dimensional digital archive is durable and unalterable, and thus can be used as a reference for monitoring degradation or restoration of works.

Some of the main motivations for reverse engineering objects or sites of cultural significance are;

- Restoration Work
- Sculpture Preservation
- Virtual Exhibits & Education
- Digital Artifacts Archive
- Conservation Monitoring
- Historical Deciphering

- Digital Reconstruction
- Scaled Physical Replicas

Since the objects may not require engineering analysis or downstream manufacturing with close tolerances, the RE solution has some flexibility in how it is applied. For example it would be desirable to have a system that could be implemented and utilized by non-engineers. Some heritage applications aimed at more analytical tasks demand that the data to be processed be of superior quality and that the results are accurately visualized. [4] Several research groups have investigated reliable, robust scanning systems that can be implemented in the restrictive environment of a museums or cultural site. Teams must work around visiting hours, confined spaces and stringent safety or security precautions. The National Research Council of Canada has undertaken dozens of these types of projects since the mid 90s. Another project by the IBM T.J. Watson Research Center involved the nightly set up a portable scanning system in order to make a digital model of Michelangelo's Florentine Pieta. Italy is a hot bed of European art pieces and historical sculptures, and the access to these pieces has lead local academics and curators to team up and deliver numerous projects dealing with 3D scanning of large, detailed objects. [2]

Arguably the most impressive, memorable and successful project entailing 3D digitization of a renowned sculpture is the Digital Michelangelo project, undertaken by a team of faculty and students from Stanford University, headed by Marc Levoy. The time period for the project was 1998-2001, the locale was the Galleria dell'Academia in Florence, Italy and the main focus piece was the well-known sculpture, David. It is commonplace that such great works of art cannot be removed from their environment or taken off public display for any extended period. The Stanford research team used a state-of-the-art laser scanner mounted on a custom built gantry to capture billions of points on the surface of the 7m tall marble sculpture. The laser revealed details as fine as the artist's chisel marks, with resolutions of less than 0.5mm. The collection of images was converted into one 3D computer model, pushing the limits of computing power with the largest model ever of its kind. "This model, requiring 32 gigabytes (of storage), will be one hundred times larger than any geometric computer model yet created with 3D scanning" said Marc Levoy. The mathematical proposition behind the rendering was a hierarchical method based on a pre-computed bounding sphere tree structure. An optical laser scanner from Cyberware was the main hardware, but for hard-to-reach spots a Faro jointed digitizing arm and small triangulation laser rangefinder made by 3D Scanners Ltd were used. [9] The three-dimensional computerized portrait of the marble sculpture allows experts to view David in otherwise impossible and likely unintended ways. This lead to a simulating discussion about the fact that the statue's gaze is anatomically distorted, probably intentionally, since Michelangelo sculpted the statue to be viewed from the side rather than head on. In actuality, to get this flawed view a person would have to be situated high up and outside the museum walls.

An even larger scale data collection and processing project was an effort by a group from Texas Tech University to generate a digital model of the Statue of Liberty consisting of 16 million points. The actual gathering of points took place over just a few days in August of 2001, but obstacles were encountered on the way to reverse engineering success. Initially 94 millions points of raw scan data were collected from 13 viewpoints around the base of the statue. Once the first full point cloud registration had been achieved, work began to determine the appropriate file size, procedures and software that would best serve the project deliverables. The original intent of the work was to product a series of horizontal sections, cut at uniform 1 ft increments, yielding just over 100 line drawings, along with the first ever produced scaled elevation drawings. Regrettably the data set had many large information gaps where the surface had been blocked from the scanner's view. A plan to 'fill-in' the holes in the data using Geomagic Studio surfacing tools required approval from the Historic American Buildings Survey. [10] Failing that, the project could only meet its completion goals by making yet another trip to the site with a new system to elevate the scanner and acquire the missing data.

6. FUTURE DIRECTIONS

For any reverse engineering task, blending the best approaches and technologies from an expanding list of options can be a daunting undertaking. A growing number of CAD or scanner service bureaus offer digitizing and reverse-engineering services, making it an accessible choice for design and manufacturing companies. Consequently, some progress has been kept at bay since in-house development of the technology is not likely. Because of the complexity of the process itself and the challenges presented by each job, analysts say reverse engineering is destined to remain a niche market. "The types of subjects that may be reverse engineered are just all over the map, and each one has different requirements regarding scanning resolution and whether the scanned image will be going into a CAD application or an animation program." Engineers shopping for 3D digitizers have hundreds of products choices from an abundance of small companies, many of which are bundled with proprietary digitizing software. The market goal should be to price hardware units low enough to "get engineers thinking in-house" and team up with proven software vendors to provide a total turnkey solution.

Reverse engineering as a topic in engineering education is also overlooked. It is hard to incorporate meaningfully into classical curriculum, in part, because it is an emerging field, whose requirements are lab-based hardware, software and computing equipment. The emergence of 'knowledge based' and 'CAD driven' reverse engineering can overcome these obstacles. Integration of RE projects with geometric modeling courses is one way to highlight the existence of workable RE techniques. The technology is accessible at this level and efforts should be made by those in any application field to avail themselves of it.

It is apparent that the trend of non-engineering industries such as entertainment taking a technology to a new level will continue with reverse engineering of physical shapes. The general population may not be increasingly exposed to the technology, but we can be sure that it is at work behind the scenes in a growing number of applications for customized products, made to suit an individual's anatomy or preferences.

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