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AMAZE

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MODULE 4
Reverse Engineering

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Authors	**Remigiusz Łabudzki, Natalia Wierzbicka, Adam Patalas, Paweł Zawadzki**
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1 *Introduction*

In today's intensely competitive global market, product enterprises are constantly seeking new ways to shorten lead times for new product developments that meet all customer expectations. In general, product enterprise has invested in CAD/CAM, rapid prototyping, and a range of new technologies that provide business benefits. Reverse engineering (RE) is now considered one of the technologies that provide business benefits in shortening the product development cycle. Figure 1.1 below depicts how RE allows the possibilities of closing the loop between what is "as designed" and what is "actually manufactured".

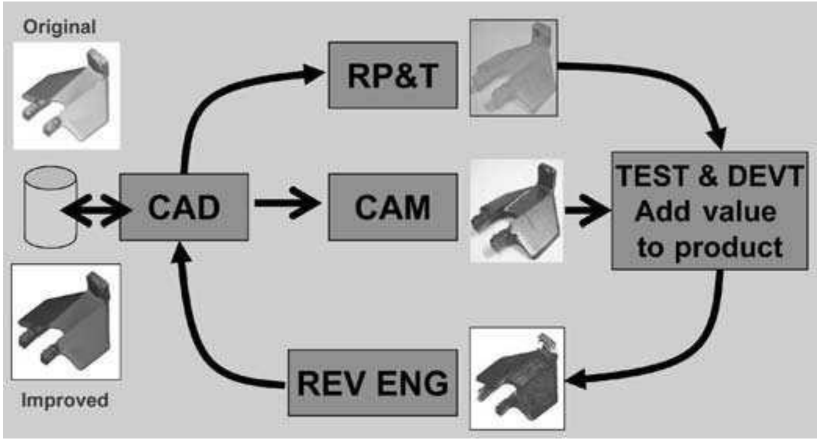

Figure 1.1 Product development cycle

1.1 *What Is Reverse Engineering?*

Engineering is the process of designing, manufacturing, assembling, and maintaining products and systems. There are two types of engineering, forward engineering (FE) and reverse engineering (RE) – figure 1.2. Forward engineering (FE) is the traditional process of moving from high-level abstractions and logical designs to the physical implementation of a system. In some situations, there may be a physical part/product without any technical details, such as drawings, bills-of-material, Or without engineering data. The process of duplicating an

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existing part, subassembly, or product, without drawings, documentation, or a computer model is known as reverse engineering (FE). Reverse engineering is also defined as the process of obtaining a geometric CAD model from 3-D points acquired by scanning/digitizing existing parts/products. The process of digitally capturing the physical entities of a component, referred to as reverse engineering (RE), is often defined by researchers with respect to their specific task [1].

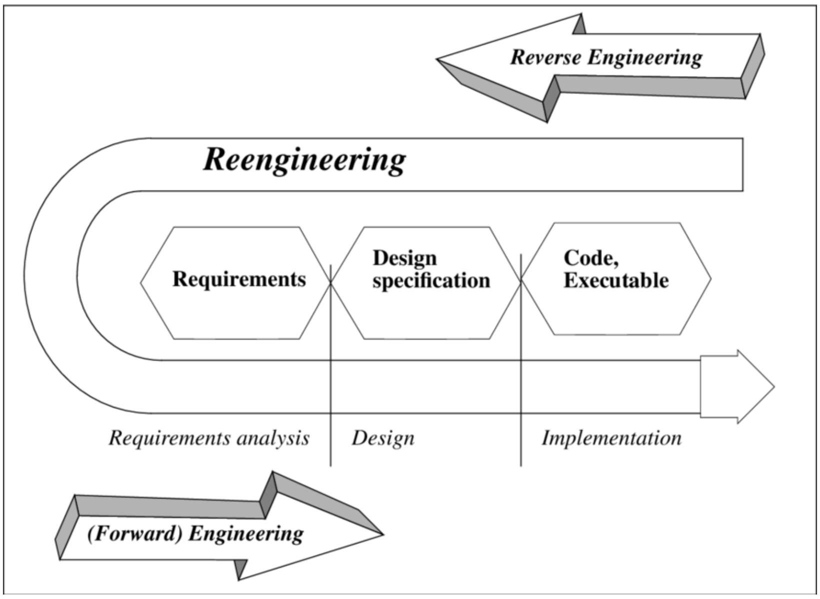

Figure 1.2 Forward Engineering (FE) vs Reverse Engineering (RE)

Abella [2] described RE as, “the basic concept of producing a part based on an original or physical model without the use of an engineering drawing”. Yau [3] define RE, as the “process of retrieving new geometry from a manufactured part by digitizing and modifying an existing CAD model”.

Reverse engineering is now widely used in numerous applications, such as manufacturing, industrial design, and jewellery design and reproduction For example, when a new car is launched on the market, competing manufacturers may buy one and disassemble it to learn

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how it was built and how it works. In software engineering, good source code is often a variation of other good Skurce code. In some situations, such as automotive styling, designers give shape to their ideas by using clay, plaster, wood, or foam rubber, but a CAD model is needed to manufacture the part. As products become more organic in shape, designing in CAD becomes more challenging and there is no guarantee that the CAD representation will replicate the sculpted model exactly.

Reverse engineering provides a solution to this problem because the physical model is the source of information for the CAD model. This is also referred to as the physical-to-digital process depicted in Figure 1.3. Another reason for reverse engineering is to compress product development cycle times. In the intensely competitive global market, manufacturers are constantly seeking new ways to shorten lead times to market a new product. Rapid product development (RPD) refers to recently developed technologies and techniques that assist manufacturers and designers in meeting the demands of shortened product development time. For example, injection-molding companies need to shorten tool and die development time drastically. By using reverse engineering, a three-dimensional physical product or clay mock-up can be quickly captured in the digital form, remodeled, and exported for rapid prototyping/tooling or rapid manufacturing using multi-axis CNC machining techniques.

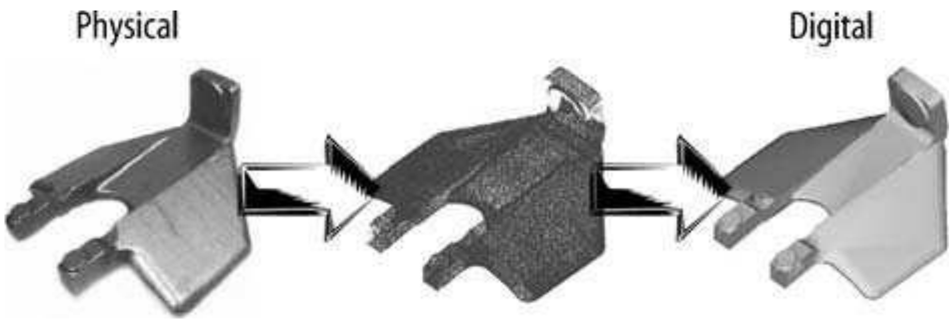

Figure 1.3 Physical-to-digital process

1.2 *Why Use Reverse Engineering?*

Following are some of the reasons for using reverse engineering:

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• The original manufacturer no longer exists, but a customer needs the product, e.g., aircraft spares required typically after an aircraft has been in servicefor several years.

• The original manufacturer of a product no longer produces the product, e.g., the original product has become obsolete.

• The original product design documentation has been lost or never existed.

• Creating data to refurbish or manufacture a part for which there are no CAD data, or for which the data have become obsolete or lost.

• Inspection and/or Quality Control–Comparing a fabricated part to its CAD description or to a standard item.

• Some bad features of a product need to be eliminated e.g., excessive wear might indicate where a product should be improved.

• Strengthening the good features of a product based on long-term usage.

• Analyzing the good and bad features of competitors' products.

• Exploring new avenues to improve product performance and features.

• Creating 3-D data from a model or sculpture for animation in games and movies.

• Creating 3-D data from an individual, model or sculpture to create, scale, or reproduce artwork.

• Architectural and construction documentation and measurement.

• Fitting clothing or footwear to individuals and determining the antropometry of a population.

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• Generating data to create dental or surgical prosthetics, tissue engineered body parts, or for surgical planning.

• Documentation and reproduction of crime scenes.

The above list is not exhaustive and there are many more reasons for using reverse engineering, than documented above.

1.3 *Reverse Engineering–The Generic Process*

The generic process of reverse engineering is a three-phase process as depicted in Figure 1.4. The three phases are scanning, point processing, and application specific geometric model development. Reverse engineering strategy must consider the following:

• Reason for reverse engineering a part

• Number of parts to be scanned–single or multiple

• Part size–large or small

• Part complexity–simple or complex

• Part material–hard or soft

• Part finish–shiny or dull

• Part geometry–organic or prismatic and internal or external

• Accuracy required–linear or volumetric

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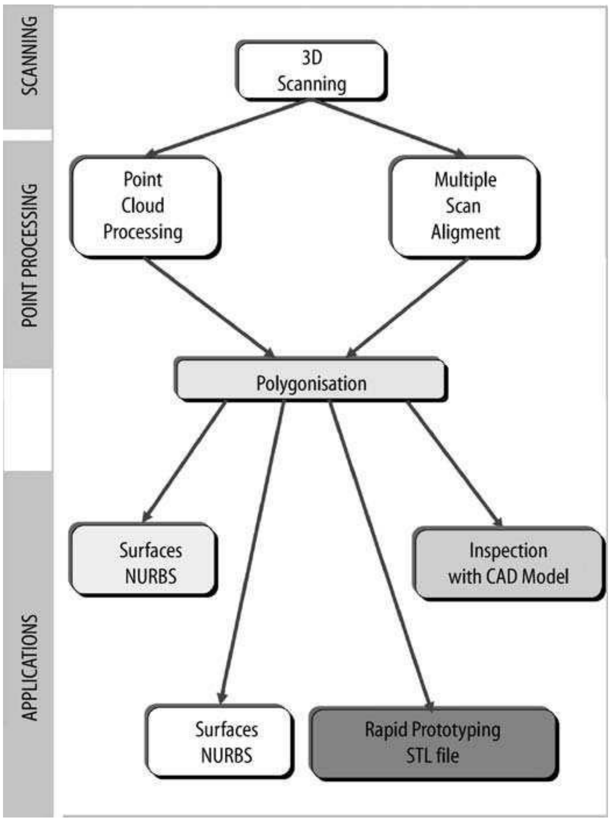

Figure 1.4 Reverse engineering – the generic process

1.4 *Phase 1–Scanning*

This phase is involved with the scanning strategy–selecting the correct Canning technique, preparing the part to be scanned, and performing the actual Canning to capture information that describes all geometric features of the part such as steps, slots, pockets, and holes. Three-dimensional scanners are employed to scan the part geometry, producing clouds of points, which define the surface geometry. These scanning devices are available as dedicated tools or as add-onsto the existing computer numerically controlled (CNC) machine tools. There are two distinct types of scanners, contact and noncontact.

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1.4.1 Contact Scanners

These devices employ contact probes that automatically follow the contours of a physical surface (Fig. 1.5). In the current marketplace, contact probe scanning devices are based on CMM technologies, with a tolerance range of +0.01 to 0.02 mm. However, depending on the size of the part scanned, contact methods can be slow because each point is generated sequentially at the tip of the probe. Tactile device probes must deflect to register a point; hence, a degree of contact pressure is maintained during the scanning process. This contact pressure limits the use of contact devices because soft, tactile materials such as rubber cannot be easily or accurately scanned.

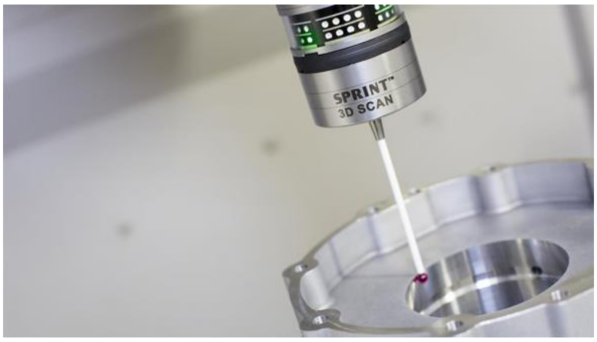

Figure 1.5 Contact scanning touch probe.

1.4.2 Noncontact Scanners

A variety of noncontact scanning technologies available on the market capture data with no physical part contact. Noncontact devices use lasers, optics, and charge-coupled device (CCD) sensors to capture point data, as shown in Figure 1.6. Although these devices capture large amounts of data in a relatively short space of time, there are a number of issues related to this scanning technology.

- The typical tolerance of noncontact scanning is within ±0.025 to 0.2 mm.

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• Some noncontact systems have problems generating data describing surfaces, which are parallel to the axis of the laser (Figure 1.7).

• Noncontact devices employ light within the data capture process. This creates problems when the light impinges on shiny surfaces, and hence some surfaces must be prepared with a temporary coating of fine powder before scanning.

These issues restrict the use of remote sensing devices to areas in engineering, where the accuracy of the information generated is secondary to the speed of data capture. However, as research and laser development in optical technology continue, the accuracy of the commercially available noncontact scanning device is beginning to improve.

The output of the scanning phase is point cloud data sets in the most convenient format. Typically, the RE software provides a variety of output formats such as raw (X, Y, Z values separated by space or commas).

Figure 1.6. Optical scanning device.

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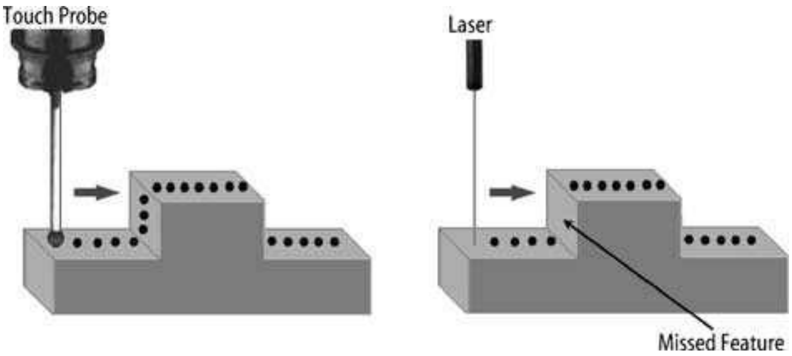

Figure 1.7. Vertical faces–touch probe versus a laser [4]

1.5 *Phase 2–Point Processing*

This phase involves importing the point cloud data, reducing the noise in the data collected, and reducing the number of points. These tasks are performer using a range of predefined filters. It is extremely important that the users have very good understanding of the filter algorithms so that they know which filter is the most appropriate for each task (Fig 1.8). This phase also allows us to merge multiple scan data sets (Fig. 1.9). Sometimes, it is necessary to take multiple scans of the part to ensure that all required features have been scanned. This involves rotating the part; hence each scan datum becomes very crucial. Multiple scan planning has direct impact on the point processing phase. Good datum planning for multiple scanning will reduce the effort required in the point processing phase and also avoid introduction of errors from merging multiple scan data. A wide range of commercial software is available for point processing.

The output of the point processing phase is a clean , merged, point cloud data set in the most convenient format. This phase also supports most of the proprietary formats mentioned above in the scanning phase.

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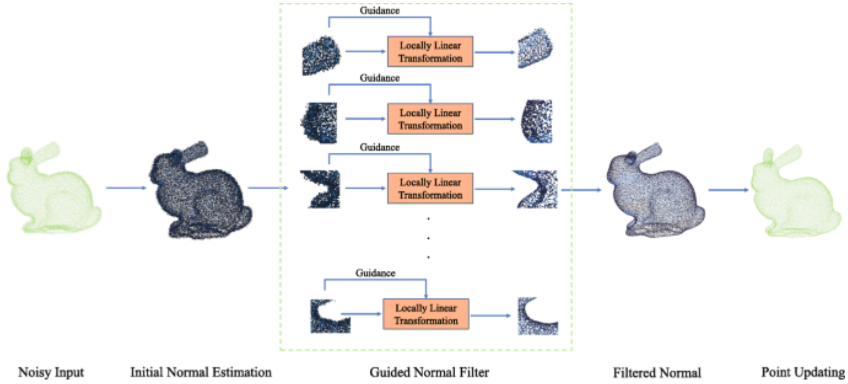

Figure 1.8 Filtering point cloud in RE

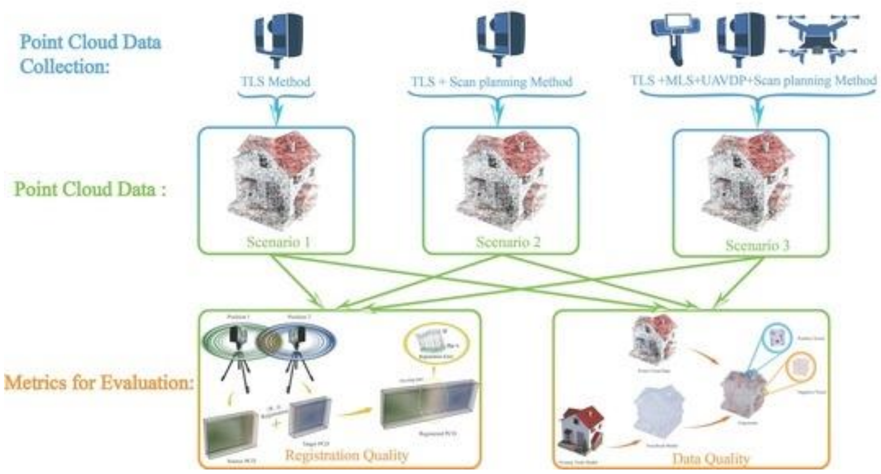

Figure. 1.9 Multiple scan planning in architecture

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1.6 *Phase 3–Application Geometric Model Development*

In the same way that developments in rapid prototyping and tooling Technologies are helping to shorten dramatically the time taken to generate physical representations from CAD models, current RE technologies are helping to reduce the time to create electronic CAD models from existing physical representations. The need to generate CAD information from physical components will are frequently throughout any product introduction process (Fig. 1.10).

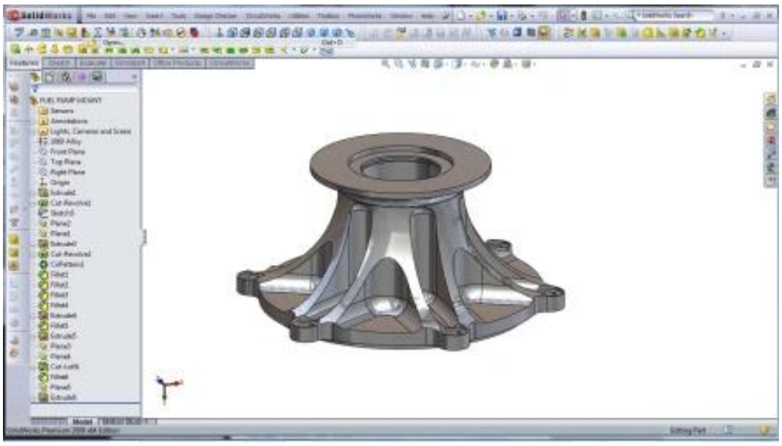

Figure 1.10 Sample of CAD model

The generation of CAD models from point data is probably the most complex activity within RE because potent surface fitting algorithms are required to generate surfaces that accurately represent the three-dimensional information described within the point cloud data sets. Most CAD systems are not designer to display and process large amounts of point data; as a result new RE module or discrete software packages are generally needed for point processing. Generating surface data from point cloud data sets is still a very subjective process, although feature-based algorithms are beginning to emerge that will enable engineers to interact with the point cloud data to produce complete solid models for current CAD environments.

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The applications of RE for generating CAD data are equally as important as the technology which supports it. A manager's decision to employ RE Technologies should be based on specific business needs.

This phase depends very much on the real purpose for reverse engineering. For example, if we scanned a broken injection molding tool to produce a new tool, we would be interested in the geometric model and also in the ISO G code data that can be used to produce a replacement tool in the shortest possible time using a multi-axis CNC machine. One can also use reverse engineering to analyze "as designed" to "as manufactured". This involves importing the as designer CAD model and superimposing the scanned point cloud data set of the manufactured part. The RE software allows the user to compare the two data sets (as designed to as manufactured). This process is also used for inspecting manufactured parts. Reverse engineering can also be used to scan existing hip joints and to design new artificial hips joint around patient- specific pelvic data. This creates the opportunity for customized artificial joints for each patient.

The output of this phase is geometric model in one of the proprietary formats such as IGES, VDA, STL, DXF, OBJ, VRML, ISO G Code, etc. This chapter defined the term "reverse engineering" followed by reasons for using reverse engineering. It also introduced the reverse engineering strategy, the three phases of the reverse engineering generic process, contact and noncontact scanning, point processing, and application geometric model development.

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2 Methodologies and Techniques for Reverse Engineering

2.1 Computer-aided Reverse Engineering

Each discipline of engineering has a different definition for RE. Computer engineers and computer scientists, for example, refer to RE when they speak of determining the algorithmic functionality of a software package when they have no prior knowledge of the original software design. Engineers and programmers attempt to develop functional block diagrams of the software through interaction with the interface and to develop high-level code descriptions from Raw machine code. This software definition is not the scope of our RE discussion. Another example of RE that might be familiar–but also outside the scope of this chapter–concerns revealing the inner workings of a machine to figure out what makes it tick. This form of RE is also a systems level approach where an engineer disassembles the item of interest to develop an understanding of the functional relationship of components or to gain insight into the types of materials used to fabricate the components. As with software RE, the goal is to develop a highlevel description of a system without a priori knowledge. These two examples are common applications that use the term RE, but we wish to emphasize that our definition of RE is not related to these examples, but is instead related to the area of computer-aided engineering (CAE).

In the late 1970s and into the 1980s, computer-aided design (CAD)–a komponent of CAE– began to revolutionize engineering disciplines. The peak of this revolution occurred in 1990 with the design of the Boeing 777; the entire aircraft was designed and preassembled through a virtual CAD) simulation. According to Boeing, the first 777 to roll out of the production hangar in 1994 was just hundredths of an inch–about the thickness of a playing card–within alignment. This precision contrasts with the half-inch alignments common with most aircraft parts before that time–an improvement of several orders of magnitude. This revolution in technology has continued into the 1990s and today with the emergencje and growth of computer-aided manufacturing (CAM). CAM is the automation of the manufacturing process itself–beyond just the design process – where machines such as computerized numerically

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controlled (CNC) mills allow precise fabrication of objects directly from CAD descriptions. With CAM, a designer can rapidly move from a conceptual CAD description to a real-world tangible object. We might use the term forward engineering—in a tongue-incheek manner—to describe this type of design, and the term CAE to describe the automation of forward engineering through CAD and CAM technologies.

CAE through CAD and CAM technologies is the automation of engineering and fabrication, where a design formalizes ideas through computer modeling and then fabricates those models into real-world objects. CARE flows in the opposite direction. CARE creates a computer model of an object through measurements of the object, as it exists in the real world. In this context, we define CARE as the reversal of CAE or the ability to generate a CAD model from a real-world tangible object (Fig. 2.1).

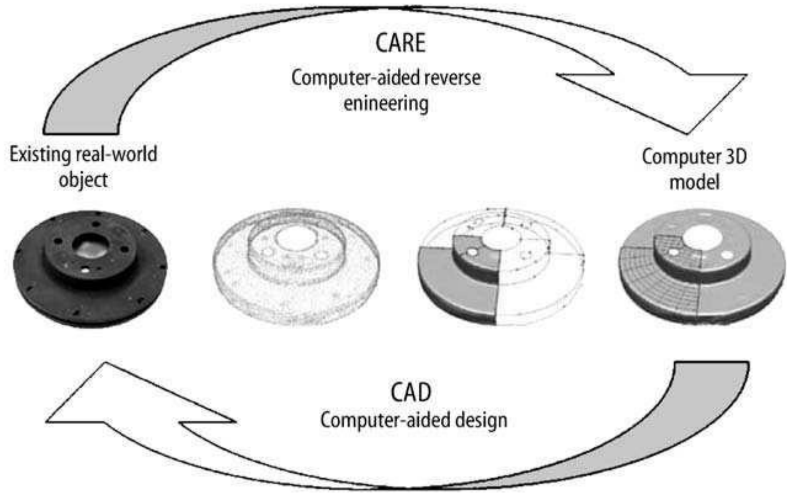

Figure 2.1 Computer-aided reverse engineering (CARE) process

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To understand the CARE steps, consider the stages shown in Figure 2.1 from left to right. The first step in the CARE process is to make measurements AT points along the surface of the brake. Each point has an x, y, and z coordinate locating the point in 3-D space. For a given object, a CARE system will measure hundreds or even thousands of such points depending on the nature of the object and the type of CARE system. The collection of these points is known as a point cloud; an example appears in the second picture from the left in Figure 2.1. In most applications, the point cloud is a sufficient description of the object. However, higher levels are possible as the remaining two pictures on the right show. The third picture from the left is a feature description of the object, in which the CARE system has detected surface edges and creases from the point cloud data. The final picture on the right is a full and complete CAD description of the object. For this description, the CARE system uses the point cloud and the detected features to fit surfaces for modeling the entire geometry of the object.

2.2 *Computer Vision and Reverse Engineering*

Computer vision bridges diverse fields from electrical engineering to computer science to cognitive psychology. Computer vision systems seek to develop computer models of the real world through processing of image data from sensors such as video cameras or–as in our case–3-D range scanners. Because computer vision is relatively new to RE, we begin this section by first investigating traditional (noncomputer vision) approaches to RE, and then use these methods as a backdrop for laser range scanners.

2.2.1 Coordinate Measuring Machines

Calipers are a common ad hoc approach to RE. These measurement devices allow engineers and machinists to determine accurate diameters, lengths, and other dimensions of objects. This approach to RE is a manual process that requires significant effort for complicated objects and surfaces. CMM technology is the first effort to automate the RE process. Before CMM and probably still popular for most simple tasks, engineers and machinists have used measurement calipers. For the disc brake, we could use calipers to measure the diameters of the various holes and cylinders that comprise the basic shape of the brake, as in Figure 2.2. Then, from these measurements, we could manually lay out a computer model of the brake

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using CAD primitives. For a simple object, this manual process of RE is straightforward, but as the complexity of the object shape increases, the basic CAD primitives such as planar and quadric surfaces are no longer suitable. A free-form surface, for example, that is nonplanar and nonquadratic [5] does not lend itself readily to characterization with just calipers. Free-form surfaces require special consideration and attention. Calipers are not practical for capturing their subtleties.

As an alternative, CMMs first appeared in the early 1960s and are a more practical means for characterizing and inspecting free-form surfaces. A CMM consists of a probe supported on three mutually perpendicular (x, y, and z) axes; each axis has a built-in reference standard. Figure 2.3 provides a conceptual view of a CMM. The probe allows accurate measurements along each axis relative to the standard. Thus, a CMM generates 3-D coordinate points as the probe moves across a surface. Operators may run a CMM in a manual mode where they maneuver the probe around an object and collect coordinate measurements, or they may program the probe to maneuver automatically on its own. This latter metod is more relevant to the CARE definition under discussion. Different CMM manufacturers offer different schemes to help operators plan the path that the probe will follow. The more advanced CMM systems allow operators to upload a CAD model of the object and then the CMM uses this model for the path planning strategy. The CMM will analyze the CAD model to identify critical points and regions such as discontinuity creases or tight spaces. Tight spaces are a point of emphasis because the probe must come in contact with or be close to the point on the surface where a measurement occurs. If the probe cannot reach the point due to extension constraints (i.e., the point is too far) or limited space (i.e., the probe is too large), then the system cannot measure at that location. The probe must touch or be near the measurement location. This constraint is the motivation for computer vision approaches to CARE because computer vision offers a more standoff measurement.

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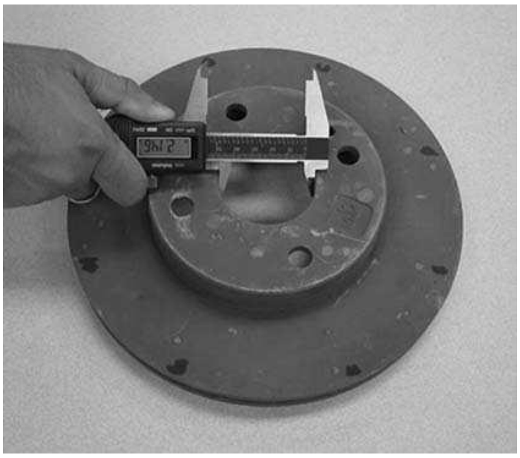

Figure 2.2 Measuring the disk brake using a calliper

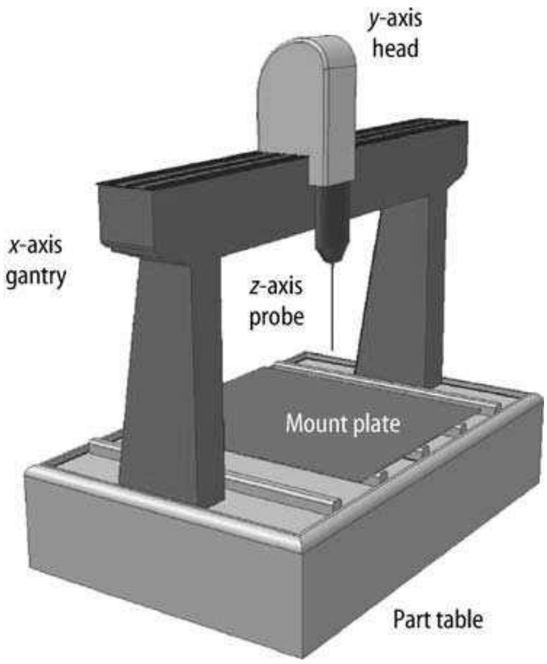

Figure 2.3 Conceptual view of a CMM that illustrates the major components of most systems

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2.2.2 Active Illumination 3-D Stereo

Computer vision attempts to develop solutions through sensors such as video cameras or other imaging-based systems [6, 7, 8]. To acquire 3-D information, the most well-known methodology that probably comes to mind is stereovision, in which two cameras operate in a manner similar to human eyes. Unfortunately, although stereo-based imaging has become useful in such applications as navigation planning and obstacle avoidance for Mars Rover missions, passive stereo does not offer the accuracy that industrial RE applications demand. The major drawback of stereovision is the need to establish correspondence between a point in one camera's image and the same point in the secondo camera's image. If we can establish this correspondence, we can construct an accurate stereo depth map, or range image, but correspondence is an elusive problem. The term passive stereo is important because it indicates that the camera in the system do not rely on active forms of illumination, except ambitne light. One way to overcome the correspondence problem is to control illuminati on in an intelligent manner and thus simplify the correspondence search. Such methods are known as active illumination stereo (or more simply active stereo) where we replace one of the stereo cameras with a well-defined light source. A laser is typically the light source of choice. Active stereo using laser-based illumination allows more accurate depth measurements than traditional passive illumination stereo. (We use the term depth measurement as an alternative to a 3-D point measurement from CMMs. At this point, the subtle nuance between these two terms is not important, but they are interchangeable because a depth measurement is a 3-D point measurement.) Although passive stereo is not viable for a CARE system, active stereo does offer potential. To understand active stereo, we should consider three popular approaches to illumination control. These major categories are (a) continuous wave modulation, (b) time-of-flight estimation, and (c) structured-light triangulation. Continuous wave systems measure depth by using a coherent light source, i.e., a laser, and measure phase differences of the light wave as it travels to and from the object. Figure 2.4 shows an example. The distance of an object from the camera is proportional to the phase difference between the transmitted wave and the returning wave.

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The accuracy of these systems correlates with the accuracy in measuring the phase differences and the wavelength of the laser. Time-of-flight methods operate similarly to radar where the system measures the time required for a laser pulse to travel to and return from an object. Figure 2.5 illustrates such a system. Highly accurate depth measurements require precision electronics to measure speed-oflight time increments. As a third option for active stereo, structured-light techniques compute depth through geometric triangulation. The camera, the object, and the light source form the triangulation geometry. See Figure 2.6. This configuration is similar to passive stereo geometry, except that we have replaced one of the cameras with a light source. The accuracy of these methods is a function of the camera resolution, geometric dimensions, and illumination precision, but the primary parameter for controlling and increasing accuracy is the camera resolution. System geometry and illumination are not as critical. Thus, structured-light systems offer a solution more practical than passive stereo in achieving the accuracy necessary for an RE system. In a later section, we will explore structured-light techniques more in depth, but first we seek to compare and contrast the benefits of active stereo to CMM.

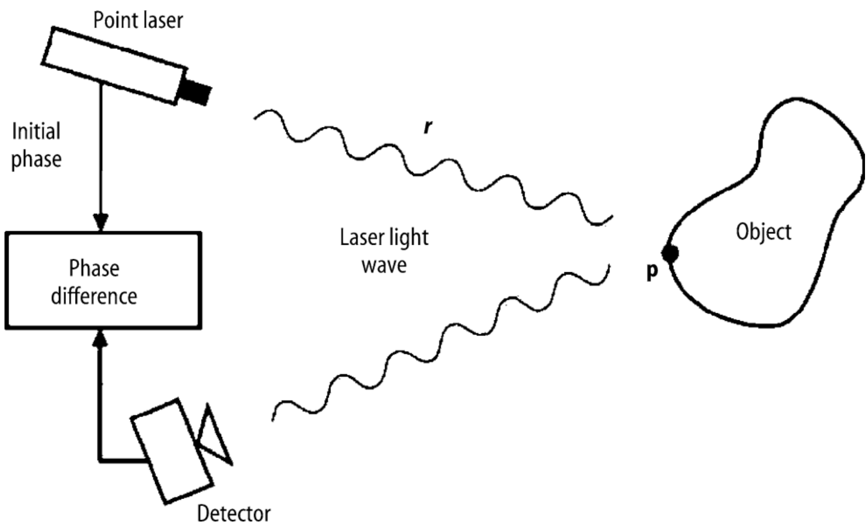

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Figure 2.4. Active stereo example of a continuous wave system. The laser travels as a light wave from the laser source to the object and back to the detector. As a wave, the laser light undergoes a phase change as it travels. The difference in phase reveals the object's distance.

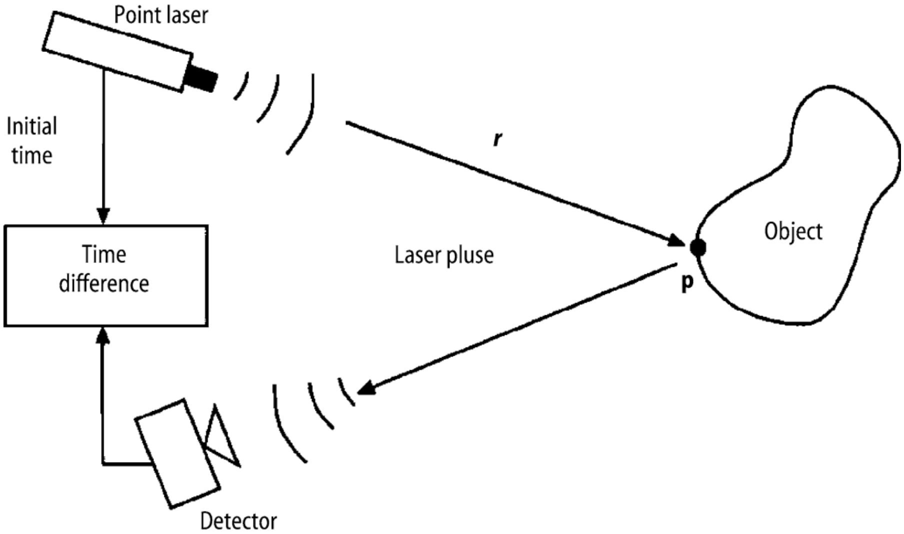

Figure 2.5. Active stereo example of a time-of-flight system. A point laser emits a pulse that is reflected from the object of interest. The difference between the initial time when the pulse was transmitted and the time that it returns to the detector correlates with the object's distance.

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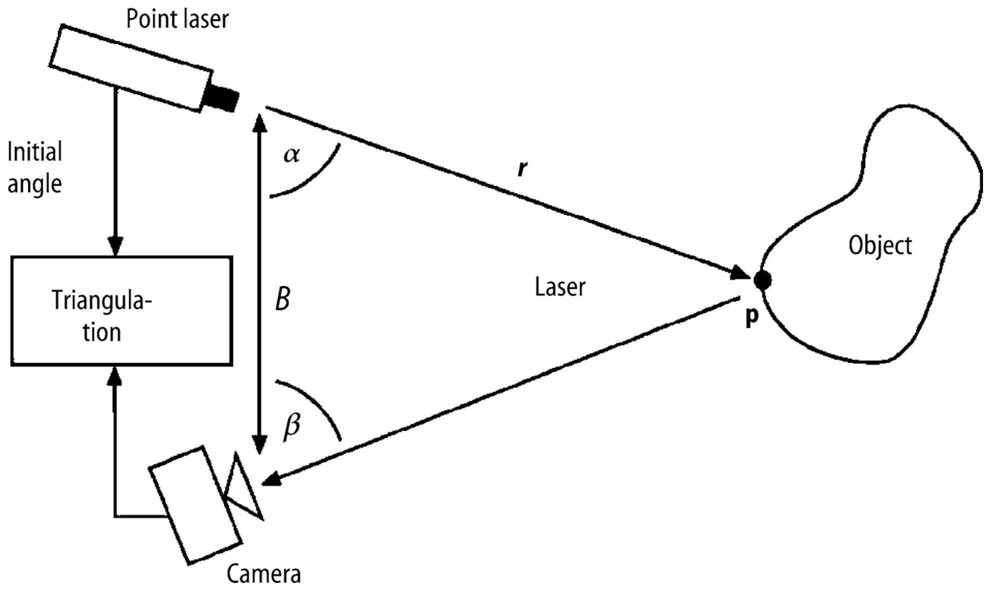

Figure 2.6. Active stereo example of a structured-light system. This example shows a triangulation-based approach where B, β, and α are typically known through system calibration.

2.2.3 Sheet-of-light Range Imaging

Sheet-of-light scanners offer the greatest speed advantage in collecting 3-D data compared to other laser scanners and thus are the most suitable for CARE applications. Their basic operation is such that the laser projects a line onto the object of interest, and triangulation among this line, the laser, and a camera field 3-D measurements. The photograph in Figure 2.7a is an example of a laser Line projecting onto a set of objects, and Figure 2.7b is an example of a system, the Ranger Scanner developed by Integrated Vision Products (IVP). In the figure, the objects are resting on a conveyor belt. This belt is one method for obtaining a full scan of an object. With the IVP Ranger, as with Rother sheet-of-light scanners, a single measurement results in a single line–a profile– of data. This profile is the 3-D data for points where the laser line falls on the object. A set of such profiles across the object

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is necessary to form a complete 3-D description of the object. Thus the conveyor belt moves the object under the laser line to scan the profiles over the entire object. If we stack the resulting profiles together, we have a 3-D model of the object. The conveyor generates profile slices of the object. Another approach is to not move the object but rather to move the scanner. Some sheet-of-light systems take this approach where usually the camera and laser are mounted on a wand. The user swipes this wand around the object of interest. With the conveyor, the spacing between the profiles is simply a function of the traveling speed of the conveyor and the acquisition rate of the scanner. With the wand, a more complicated tracking system is necessary to determine the interprofile relations. Commercial solutions range from magnetic position trackers to CMM probes.

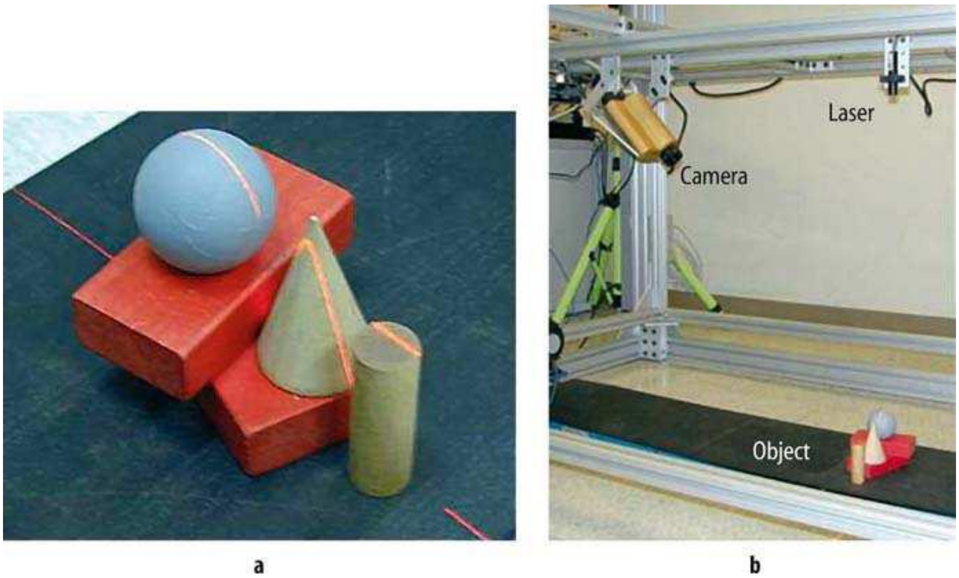

Figure 2.7 Examples of a sheet-of-light system. (a) The laser sheet casts a line on the objects under measurement. (b) This system is the IVP Ranger Scanner

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As for accuracy, the geometry defined in Figure 2.6 and the resolution of the camera govern the system. The most common arrangement is for the view angle α to be in the 30–60° range, and camera resolutions are of the order of 512 × 512 pixels or greater. These pixel resolutions correlate with more than nine bits of range resolution. As the view angle α increases toward 90° or decreases toward zero, the range accuracy decreases. At these extreme viewing angles, the camera has difficulty detecting the positional changes in the laser. First, let us consider a zero view angle. If the object surfaces are planar and perpendicular to the laser plane, the camera will not see the laser because of the oblique angle, but this angle yields the best projection for depth changes. Secondly, consider the 90° angle. With this view, the offset camera is almost looking straight down the laser plane. The camera detects the laser at the same position regardless of depth changes on the object's surface. This view offers the worst projection to the camera, but it gives the camera the best views of the laser reflection. Thus, the 30–60° range balances these two issues of no oblique viewing and projection resolution. This trade-off is also a function of the baseline distance B between the camera and the laser. As in traditional passive stereo, this distance should be of the order of the same magnitude as the range increments of interest.

The final problem we consider is occlusion, which is a common problem with computer vision systems. More specifically, the problem is known as self-occlusion where a part of an object occludes the viewing of another part of the same object. A sphere is a simple but not necessarily obvious example. When a camera views a sphere, the camera is able to image the front side, but it cannot image the reverse side. The front occludes the back. Shapes that are more complicated than a sphere have more intricate occlusions. Because the camera and the laser must view the object, a sheet-of-light range scanner has two possibilities for occlusions. As Figure 2.8 illustrates, the camera and laser cannot view the same surfaces of the object. The camera may image a surface that self-occlusion does not allow the laser to illuminate. Conversely, the laser may illuminati a surface that self-occlusion hides from the camera. A variety of strategies are possible to minimize occlusions, but we cannot eliminate the problem, as the simple sphere example demonstrates. In the next section, we discuss a pipeline for

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building CAD models using laser range scanners. We specifically discuss multiple views as a necessary solution to occlusion.

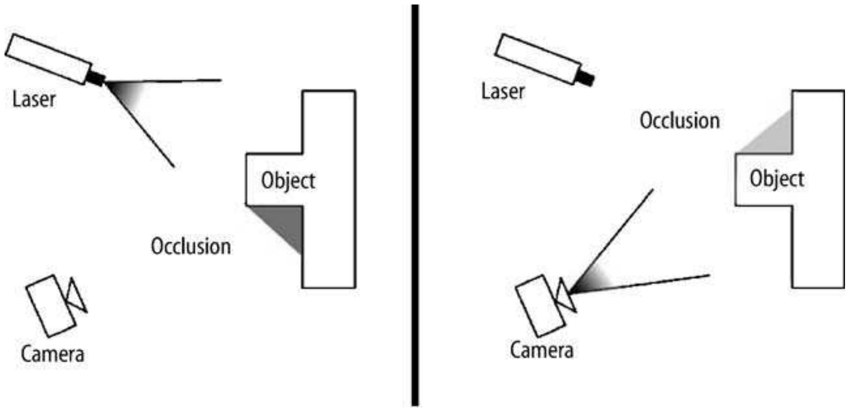

Figure 2.8. The occlusion problem with a sheet-of-light scanner. The object may occlude both the laser and the camera from viewing different surfaces on the object.

2.3 *Scan data processing*

2.3.1 Data Collection

The first step for a CARE scanner is data collection. Sheet-of-light systems are probably best suited for the CARE application. Figure 2.9. Block diagram of a CARE system based on a laser range scanner.

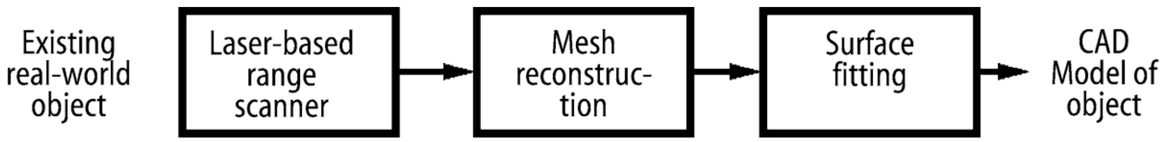

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Figure 2.9. Block diagram of a CARE system based on a laser range scanner

The first topic is calibration. Figure 2.10 demonstrates how calibration allows transforming a range image into a 3-D point cloud.

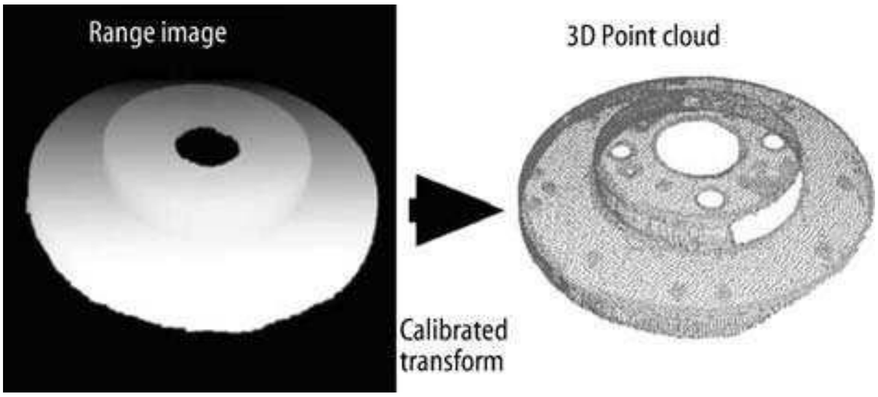

Figure 2.10. Example of a range image for the brake. The gray level of a pixel in the left image represents the distance between the brake and the sheet-of-light scanner. The darker pixels are farther away. If we calibrate the scanner, we can transform this range image into a 3-D point cloud, as shown on the right. The points (dots) exist in 3-D and each have x, y, and z coordinates.

After calibration, our next important topic is view registration. Figure 2.11 illustrates how at least two views are necessary to collect measurements of the en tire brake. If the scanner is on one side of the brake, small portions of the other side are occluded. The challenge with multiple views, however, is that we must now register the subsequent coordinate systems.

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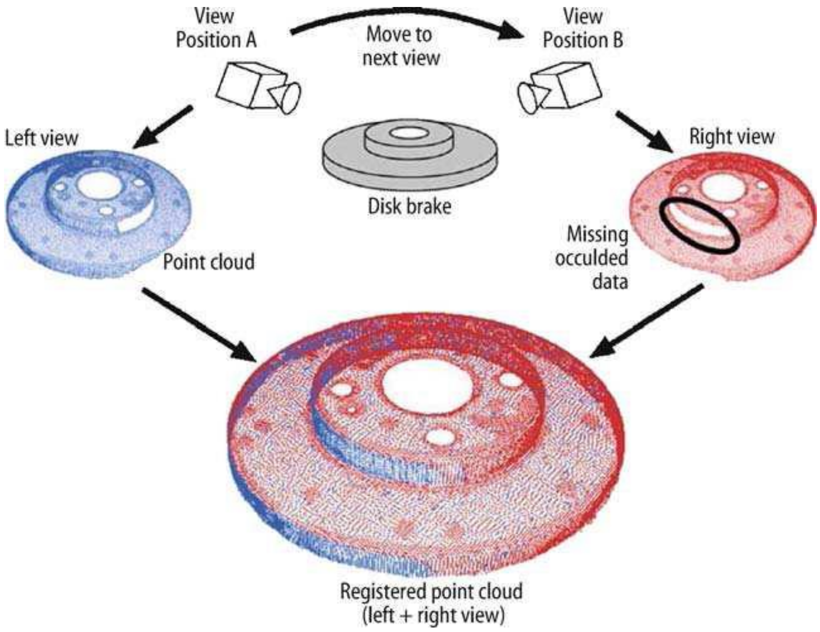

Figure 2.11. Multiple view scanning and registration overcome occlusions. Part of the brake is excluded in each of the views above. When these views are registered together, one view fills the occluded regions of the other view.

2.3.2 Mesh Reconstruction

Without much thought, most people initially consider mesh re construction trivial, and it probably is trivial for the human mind, but automatic re construction by a computer is not so easy. Hoppe et al. (1992) first addressed this topic for the general case of an unorganized point cloud. Since then, many researchers have presented their solutions, and a survey appeared in [5]. Figure 2.12 illustrates mesh reconstruction.

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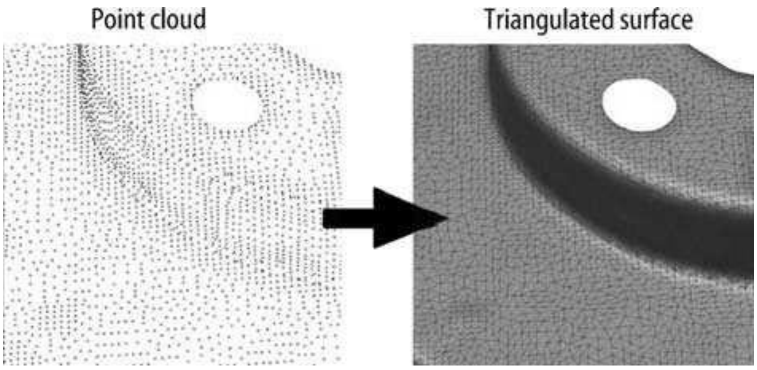

Figure 2.12. Reconstruction recovers the triangulated surface from the 3-D point cloud data

This figure is a zoom view of the disc brake to show the triangle mesh recovered from the point cloud. Triangles are a default standard as a surface primitive for a variety of reasons, but mainly they simplify computer visualizations because they have guaranteed convexity and thus are useful as a first-order approximation of an object.

For reconstruction, sampling defines the number of points in the point Cloud and their relative distance to each other (i.e., their density) on the object. Sampling is a trade-off between data set size and object coverage. A computer can more readily store and manipulate a smaller data set, but a larger set more accurately captures the fidelity of the object. Undersampling leads to incomplete and inaccurate models, but oversampling tends to overwhelm computing resources. Mesh reconstruction algorithms must define their sampling requirements, and users must tailor their CARE applications accordingly. Additionally, inherent in sampling is measurement error. Although this error is a data acquisition problem, most mesh reconstruction algorithms take this problem into account to minimize the effects of such terror.

A reconstruction algorithm requires a strategy to handle multiple views and their overlap. The third factor is missing data, which lead to holes in the mesh. These holes are not topological holes as with the doughnut but gaps in the mesh like cutouts on a sheet of paper.

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Generally, researchers have developed two categories of mesh reconstruction algorithms to deal with these factors of topology, overlap, and missing data. These categories are surface based such as presented by [9] and volumetric-based methods such as developed by [10].

2.3.3 Surface Fitting

Once we have a first-order approximation of the object from mesh reconstruction, the final stage of the pipeline is to generate higher order descriptions that are more appropriate for CAD applications. In some cases, a triangle mesh itself is sufficient as the final product of a CARE scanner. In other cases, parametric representations such as no uniform rational B-splines (NURBS) are necessary. Broadly label this final stage as surface fitting, but in practice, it takes many forms and is highly dependent on the CARE application. Eck and Hoppe [11] present a method for the recovery of splines from range scans, and their paper demonstrates the challenges that we outline.

For most complex objects, a single parameterized surface is not realizable and not practical for the entire object. Rather, we must divide the object into surface patches and then model each subsequent patch with its own parameterized surface. Thus, our first task is to segment the object into appropriate patches and then parameterize those patches individually. The major challenge is identifying appropriate patches, particularly, because parameterized surfaces assume a rectangular structure. Rectangles do not fit the arbitrary boundaries that often occur with patch selection. As a result, an additional step must trim the surface to these boundaries. Both direct and iterative optimization solutions are common. Figure 2.13, is a simple illustration of surface fitting for the now familiar brake. In this figure, we use feature detection of surface discontinuities to serve as the patch boundaries and then fit NURBS to the resulting patches. This figure concludes this chapter and finalizes the CARE procedure, originally shown in Figure 2.1.

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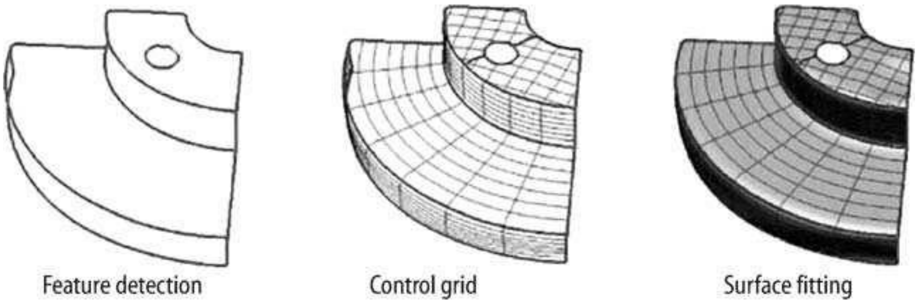

Figure 2.13. Typical surface fitting sequence.

The leftmost image shows the feature detection to establish potential surface discontinuities. The next image to the right shows the control grid to support the surface fitting process. Finally, the rightmost image shows the result of fitting a higher order surface to the measurement data.

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3 Reverse Engineering–Hardware

3.1 *Introduction*

Reverse engineering (RE) is generally defined as a process of analyzing an object or existing system (hardware and software) to identify its components and their interrelationships and to investigate how it works to redesign or produce a copy without access to the design from which it was originally produced (Wikipedia, 2005). In areas related to 3-D graphics and modeling, RE technology is used for reconstructing 3-D models of an object in different geometric formats. RE hardware is used for RE data acquisition, which for 3-D modelling, is the collection of geometric data that represent a physical object. There are Tyree main technologies for RE data acquisition: contact, noncontact and destructive. Outputs of the RE data acquisition process are 2-D cross-sectional images and point clouds that define the geometry of an object. RE software is employed to transform the RE data produced by RE hardware into 3-D geometric models. The final outputs of the RE data processing chain can be one of two types of 3-D data: (i) polygons or (ii) NURBS (non uniform rational B-splines). Polygon models, which are normally in the STL, VRML, or DXF format, are commonly used for rapid prototyping, laser milling, 3-D graphics, simulation, and animations. NURBS surfaces or solids are frequently used in computer-aided design, manufacturing, and engineering (CAD-CAM-CAE) applications.

In this chapter, hardware and software for RE are presented. Commercially available RE hardware based on different 3-D data collection techniques is briefly introduced. The advantages and disadvantages of various data acquisition methods are outlined to help in selecting the right RE hardware for specific applications. In the RE software section, end-use RE applications are classified and typical commercial RE packages are reviewed. The four RE phases used in a RE data processing chain are highlighted, and the fundamental RE operations that are necessary for completing the RE data processing chain are presented and discussed in detail.

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3.2 *Reverse Engineering Hardware*

3.2.1 Contact Methods

Contact methods use sensing devices with mechanical arms, coordinate measurement machines (CMM), and computer numerical control (CNC) machines, to digitize a surface (Fig. 3.1). There are two types of data collection techniques employed in contact methods:

1. point-to-point sensing with touch-trigger probes and

2. analogue sensing with scanning probes.

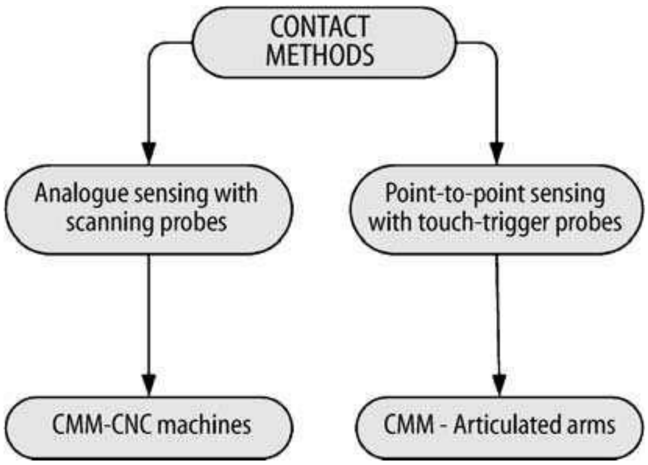

Figure 3.1. RE hardware classification–contact methods

In the point-to-point sensing technique, a touch-trigger probe is used that is installed on a CMM or on an articulated mechanical arm to gather the coordinate points of a surface. A manually operated, articulated mechanical arm with a touch-trigger probe allows multiple

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degrees of freedom (DOF) of movement to collect the measurement points (Figure 3.2). A CMM with a touch-trigger probe can be programmed to follow planned paths along a surface. A CMM provides more accurate measurement data compared to the articulated arm. However, the limitation of using CMM is the lack of number of DOF so that a CMM Carnot be used to digitize complex surfaces in the same way as an articulated arm.

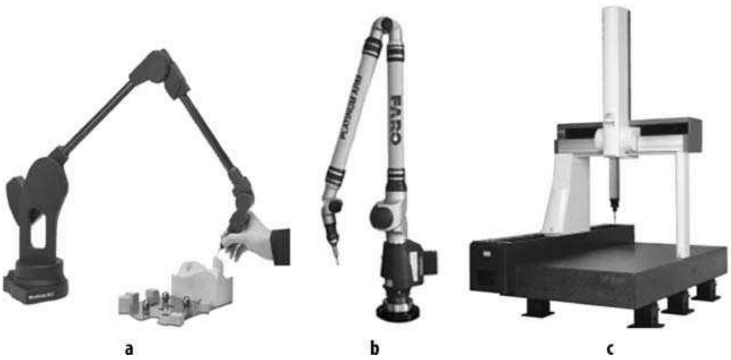

Figure 3.2. (a) MicroScribe MX Articulated Arm from Immersion Corporation, (b) Faro Arm–Platinum articulated arm from FARO Technologies, (c) Mitutoyo CMM machine–CRA Apex C model 2005)

In analogue sensing, a scanning probe is used that is installed on a CMM Or CNC machine (Figure 3.3). The scanning probe provides a continuous deflection output that can be combined with the machine position to derive the location of the surface. When scanning, the probe stylus tip contacts the feature and then moves continuously along the surface, gathering data as it moves. Therefore, throughout the measurement, it is necessary to keep the deflection of the probe stylus within the measurement range of the probe. The scanning speed in analogue sensing is up to three times faster than in point-to-point sensing.

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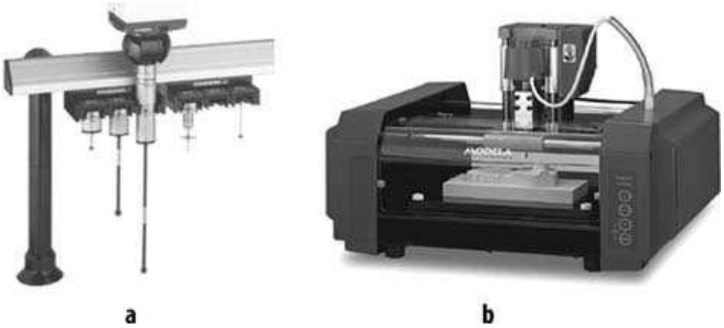

Figure 3.3. (a) SP25M scanning probes from Renishaw, (b) Roland DGA Corp. MDX-15/20 scanning and milling machine, using the Roland Active Piezo Sensor for 3-D scanning.

3.2.2 Noncontact Methods

In noncontact methods, 2-D cross-sectional images and point clouds that represent the geometry of an object are captured by projecting energy sources (light, sound, or magnetic fields) onto an object; then either the transmitted or the reflected energy is observed. The geometric data for an object are finally calculated by using triangulation, time-of-flight, wave-interference information, and image processing algorithms. There is no contact between the RE hardware and an object during data acquisition.

There are different ways to classify RE hardware that uses noncontact RE methods for data acquisition. These classifications are based on the sensor technologies (Tamas et al. 2005) or data acquisition techniques [12] employed. Figure 3.4 presents a classification of noncontact RE hardware based on data acquisition techniques. The advantages and disadvantages of noncontact methods compared to contact methods are as follows.

Advantages:

- no physical contact;

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- fast digitizing of substantial volumes;

- good accuracy and resolution for common applications;

- ability to detect colours;

- ability to scan highly detailed objects, where mechanical touch probes May be too large to accomplish the task.

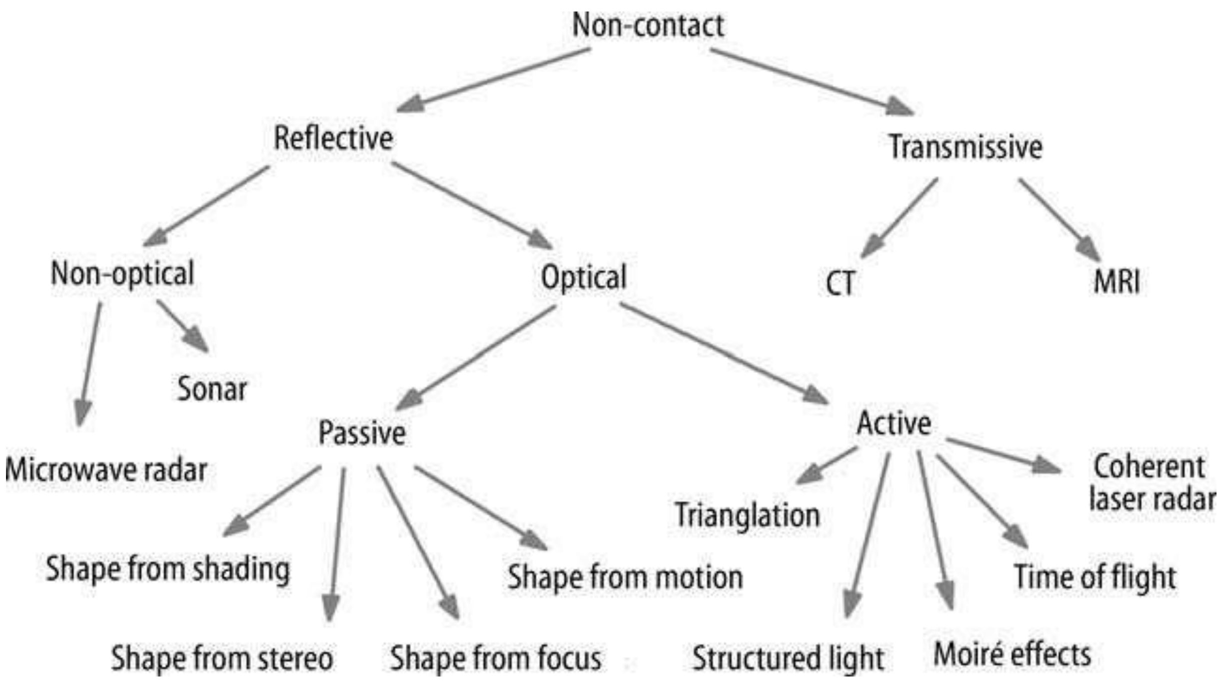

Figure 3.4. RE hardware classification–noncontact methods

Disadvantages:

- possible limitations for coloured, transparent, or reflective surfaces;

- lower accuracy.

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3.2.2.1 *Optical Techniques - Triangulation*

Most laser scanners use straightforward geometric triangulation to determine the surface coordinates of an object. Triangulation is a method that employs locations and angles between light sources and photosensitive devices (CCD–charge-coupled device camera) to calculate coordinates. Figure 3.5. shows two variants of triangulation schemes using CCD cameras: single and double CCD camera. In a single camera system, a device transmits a light spot (or line) on the object at a defined angle. A CCD camera detects the position of the reflected point (or line) on the surface. In a double camera system, two CCD cameras are used. The light projector is not involved in any measuring functions and may consist of a moving light spot or line, moving stripe patterns, or a static arbitrary pattern [13].

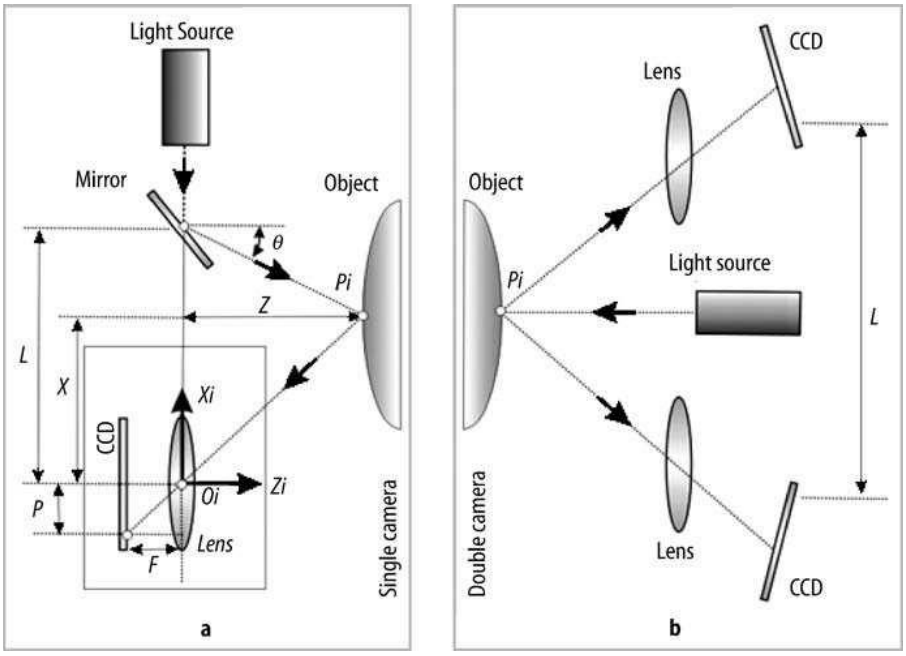

Figure 3.5. Triangulation methods: (a) single and (b) double camera arrangement

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Optical Techniques - Structured Light

In structured-light techniques [14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24], a light pattern is projected at a known angle onto the surface of interest and an image of the resulting pattern, reflected by the surface, is captured. The image is then analyzed to calculate the coordinates of the data point on the surface.

A light pattern can be (i) a single point; (ii) a sheet of light (line); and (iii) a strip, grid, or more complex coded light [25] (Figure 3.6, Figure 3.7).

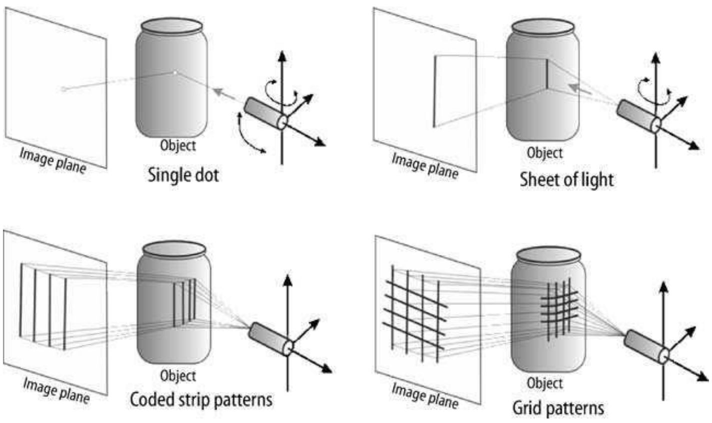

Figure 3.6. Different light patterns used in structured-light techniques

The most commonly used pattern is a sheet of light that is generated by fanning out a light beam. When a sheet of light intersects an object, a line of light is formed along the contour of the object. This line is detected and the X,Y,Z coordinates of hundreds of points along the line are simultaneously calculated by triangulation. The sheet of light sweeps the object as the linear slide carrying the scanning system moves it in the X direction while a sequence of images is taken by the camera in discrete steps. An index number k is assigned to each of the images in the order they are taken. Therefore, each k corresponds to the X position of the sheet of

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light. For each image k, a set of image coordinates (i, j) of the pixels in the illuminated stripe is obtained. The triples (i, j, k)'s are the range image coordinates; they are transformed to (x, y, z) world coordinates using a calibration matrix.

To improve the capturing process, a light pattern containing multiple strips is projected onto the surface of an object. To distinguish between different strips, they must be coded approximately so that the correspondence problem is solved without ambiguity. Structured-light systems have the following strong advantages compared to laser systems, and these features have resulted in favoring structured-light systems for digitizing images of human beings:

- the data acquisition is very fast (up to millions of points per second)

- colour texture information is available

- structured-light systems do not use a laser.

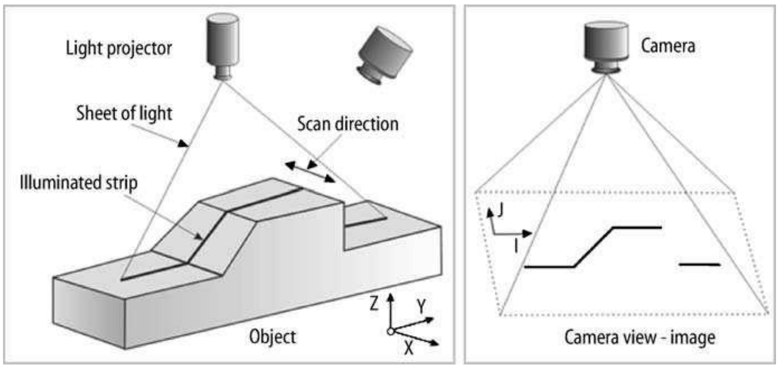

Figure 3.7. 2-D image acquisition in the structured-light technique using a sheet-of-light pattern

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Optical Techniques - Interferometry (Moiré Effects)

The interferometry technique is well known in dimensional inspection as well as in flatness and deformation measurements [26, 27, 28]), in which structured-light patterns are projected onto a surface to produce shadow moiré effects [29, 30]. The light contours produced by moiré effects are captured in an image and analyzed to determine distances between the lines. This distance is proportional to the height of the surface at the point of interest, and so the surface coordinates can be calculated.The moiré technique gives accurate results for 3-D reconstruction and measurement of small objects and surfaces. However, it has limitations for larger objects because precision is sacrificed for range. Figure 3.8. shows the formation of moiré fringes by superimposing a line pat tern with concentric circles and two other line patterns that vary in line sparing and rotation.

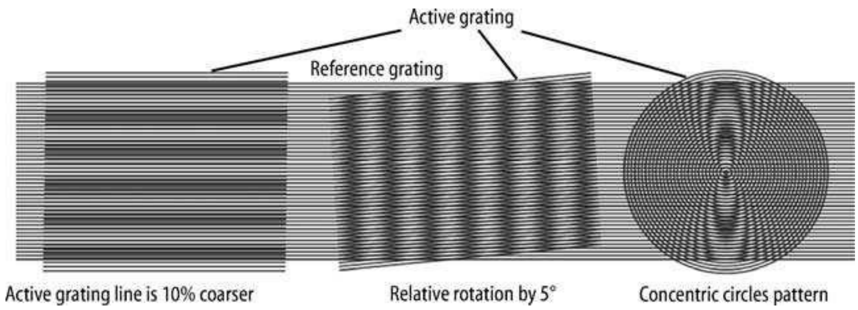

Figure 3.8. Formation of moiré fringes

Optical Techniques - Time of Flight (TOF)

The principle behind all time-of-flight (TOF) [18, 31, 32, 33, 34] implementations is to measure the amount of time (t) that a light pulse (i.e., laser electromagnetic radiation) takes to travel to the object and return. Because the speed of light (C) is known, it is possible to

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determine the distance traveled. The distance (D) of the object from the laser would then be equal to approximately one half of the distance the laser pulse traveled: D = C × t/2.

Figure 3.9 illustrates in block diagram form how a time-of-flight laser scanner works. For all practical purposes, the angle θ is very small and thus has no effect on the accuracy of the TOF distance measurement. The high velocity of light allows TOF scanners to make hundreds, or even thousands of measurements per second. The advantage of TOF techniques is that they can digitize large, distant objects such as buildings and bridges. The accuracy of RE hardware based on TOF is reasonable and approximately between a few millimeters and two Or three centimeters for long-range scanners. The accuracy depends on the pulse width of the laser, the speed of the detector, and the timing resolution; the shorter the pulse and the faster the detector, the higher the accuracy of the measurement.

The main disadvantage is that TOF scanners are large and do not capture an object’s texture, only its geometry. They are not practical for fast digitization of small and medium-sized objects. Moreover, it takes time to complete the digitization process because the object (or environment) has to be swept Turing scanning.

A variation on the TOF method is the phase shift method for determining distance measurements. Distance is computed by comparing the phase shift between an emitted wavelength and the received light. The Surphaser Model 25 developed by Surphaser Inc. (2005) is a typical commercial system. The accuracy of a phase-shift system is higher than that of traditional TOF machines. The range accuracy of the Surphaser Model 25 is 25 µm, and the angular accuracy is 0.003°. An important consequence of using phase-shift detection is that the system uses a single line of sight for its work. This means that the laser light travels the same path from the scanner to the surface and back again which enables scanning the inside of holes, cavities, and concave surfaces.

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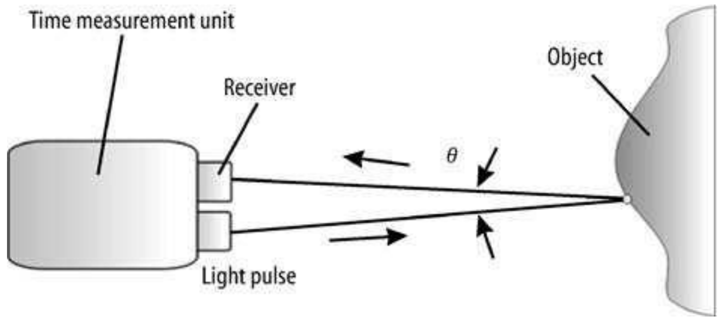

Figure 3.9. Principle of TOF scanners

Optical Techniques - Passive Methods

Passive methods reconstruct a 3-D model of an object by analyzing the images to determine coordinate data. It is similar to (active) structured-light methods in its use of imaging frames for 3-D reconstruction; however, in passive methods, there is no projection of light sources onto the object for data acquisition.

There are many different passive methods, including shape from shading, shape from stereo, shape from motion, shape from focus/defocus, shape from silhouette, and volumetric reconstruction. The typical passive methods are shape from shading [35, 36, 37, 38, 39, 40, 41,42] and shape from stereo [43, 44].

Shapes from shading (SFS) methods are used to reconstruct a 3-D representation of an object from a single image (2-D input) based on shading information. The first SFS technique was developed by Horn in the early 1970s [35, 36]. These are the main disadvantages of this metod [45]:

- the shadow areas of an object cannot be recovered reliably because they do not provide enough intensity information;

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- the method cannot be applied to general objects because it assumes that the entire surface of an object has the same reflectance;

- the method is very sensitive to noise because the computation of surface gradients is involved.

Shape from stereo or stereovision refers to the extension of SFS to a class of methods that use two or more images from different viewpoints for shadingbased 3-D shape recovery. Normally, two cameras are coordinated to generale 3-D information about an object by automatically finding corresponding features in each of the two images; then triangulation is used to measure the distance to objects containing these features by intersecting the lines of sight from each camera to the object. Compared to SFS methods, there is improved accuracy. However, finding correspondence between images is extremely difficult and can produce erroneous results from mismatches.

To solve the problem of finding correspondence, stereovision techniques can be combined with colour structured-light techniques for 3-D range data acquisition [19].

Although they require very simple hardware, passive methods do not produce accurate 3-D data. Active optical methods can overcome many of of the problems in passive methods and thus result in more accurate solutions.

Optical Techniques - Coherent Laser Radar

Recently, the advent of a new type of laser radar frequency-modulated coherent laser radar (FMCLR), created a new generation of FMCLR instruments. They can measure large-scale geometry precisely. A typical commercial RE machine in this category is a MetricVision system (MV224 and MV260 models) from Metris (2005). The accuracy (2σ) of the MetricVision system is 16 µm at 1 m, 100 µm AT 10 m, and 240 µm at 24 m. The MetricVision system operates by using a sensor to direct a focused invisible infrared laser beam to a point and coherently processes the reflected light. As the laser light travels to and from the target, it also travels

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through a reference path of calibrated optical fibre in an environmentally controlled module. The two paths are combined to determine the absolute range to the point. A very wide laser-modulation bandwidth (100 GHz) makes precise measurement possible on a millisecond timescale. The distance measurement is then combined with positional information from two precision encoders to determine a point on a surface in space.

3.2.2.2. Transitive Techniques

Computerized tomography (CT) is a powerful transmissive approach for 3-D reconstruction. CT has revolutionized the medical diagnostic field since the 1970s [46, 47, 48]. It has also been called computerized axial tomography (CAT), computerized transaxial tomography (CTAT), and digital axial tomography (DAT). CT is a nondestructive method that allows three-dimensional visualization of the internals of an object. It provides a large series of 2-D X-ray cross-sectional images taken around a single rotational axis.

Figure 3.10 presents the CT working principle of generating 2-D cross-sectional images. By projecting a thin X-ray or Y-ray beam through one plane of an object from many different angles and measuring the amount of radiation that passes through the object along various lines of sight, a map of attenuation coefficients (a density map or cross-sectional image) for the scanned surface is reconstructed.

CT is widely used for medical applications; however, it has been extended and adapted to a wide variety of industrial and 3-D modelling tasks [49, 50, 51, 52, 53]). Today, industrial CT 49, 54, 55, 56] and related technologies (digital computed laminography) [57, 58, 59] are commercially available and specialized for industrial applications. High-resolution X-ray CT and micro CT scanners can resolve details as small as a few tens of microns, even when imaging objects are made of high-density materials. It is applicable to a wide range of materials, including rock, bone, ceramic, metal, and soft tissue.

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Magnetic resonance imaging (MRI) (Donald et al. 2004[60]; Mark and Richard 2003[61]) is a state-of-the-art imaging technology that uses magnetic fields and radio waves to create high-quality, cross-sectional images of the body without Rusing radiation. When hydrogen protons in the human body are placed in a strong magnetic field, by sending in (and stopping) electromagnetic radio-frequency pulses, these protons emit signals. These signals are collected and processed to construct cross-sectional images. Compared to CT, MRI gives superior quality images of soft tissues such as organs, muscle, cartilage, ligaments, and tendons in many parts of the body.

CT and MRI are powerful techniques for medical imaging and reverse engineering applications; however, they are the most expensive in terms of both hardware and software for data processing.

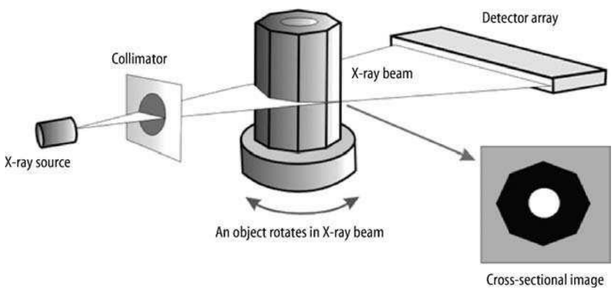

Figure 3.10. Working principle of the CT scanner

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4 *Application of Reverse Engineering*

Reverse engineering is justified to be used primarily where there is a need to duplicate the structure of an object that already physically exists. However, it is used when there is no form of recording the structure of an existing object that could constitute the basis for its production. In engineering work, it may involve both the construction of new products and the design of spare parts for used elements. It is most often used in technical industries, such as the aviation, automotive, shipbuilding and medical industries [61].

It enables the examination of objects or competitive products in order to determine how they operate, the methods and methods used in their construction and the costs of their production. Therefore, it allows obtaining key information enabling the secondary construction of the tested products. In industry, it also makes it possible to recreate device documentation and determine the composition of components of a specific object. Creating duplicates also enables the construction of models on which it is possible to perform broadly understood numerical analyzes of behaviour under the influence of changing operating conditions, as well as to test the strength of individual elements and their entire assemblies.
In IT fields, it is used to reproduce source program codes using their executable codes [61].

Recently, the development of reverse software engineering has also been visible. It includes processes related to the analysis of both the structure and operation of various types of computer programs (both those controlling the operation of network and industrial devices, as well as those intended for mobile devices, servers and personal computers[6].

4.1 *Applications in Mechanical Industries*

Reverse engineering finds wide applications in mechanical industries, serving various purposes. It is used to create a 3D model of a physical part when documentation is lost, maintain digital 3D records of products, assess competitor products, analyze product workings, inspect and compare actual geometry with CAD models, and measure tool wear.

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Applications of Reverse Engineering in Mechanical Engineering

1. Creation of 3D models of existing parts [61]:
   - Digital documentation: Reverse engineering can be used to scan and create 3D models of existing parts that lack technical documentation. This enables digital archiving and facilitates product data management.
   - Modification and improvement of existing designs: 3D models obtained from reverse engineering can be used as a basis for modifying and improving existing designs. This allows for faster and cheaper implementation of design changes.
   - Analysis and optimization: 3D models can be used for structural analysis, fluid flow simulation, and other engineering analyzes. This allows for the optimization of designs for performance and safety.

2. Production of spare parts [62]:
   - Prototyping and manufacturing: Reverse engineering enables rapid prototyping and manufacturing of spare parts for machines and devices that have been discontinued.
   - Repair and regeneration: 3D models obtained from reverse engineering can be used for 3D printing or manufacturing molds for casting damaged or worn parts.
   - Customization and personalization: Reverse engineering allows for the customization and personalization of spare parts to individual customer needs.

3. Development of new products [63]:
   - Benchmarking and competitor analysis: Reverse engineering can be used to analyze competitor products, which allows for identifying their strengths and weaknesses and drawing inspiration for designing your own products.
   - Innovation and improvements: Researching existing design solutions can be a starting point for innovation and developing new, improved products.
   - Intellectual property protection: Reverse engineering can be used to analyze potential intellectual property infringements.

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4. Reverse engineering in research processes [64]:

- Failure analysis: Reverse engineering can be used to analyze failed components to identify the causes of failure and develop preventive solutions.
- Materials and process research: Reverse engineering enables the study of the structure of materials and the analysis of technological processes used to manufacture components.
- Development of new methods and tools: Reverse engineering creates opportunities for the development of new methods and tools to support design and manufacturing.

4.1.1 CASE STUDY

The article "Application of reverse engineering techniques in mechanics system services" by Michal Dúbravþík and Štefan Kender [65] discusses the use of reverse engineering techniques in the servicing of mechanical systems. Damage of machine parts is a serious problem. It affects production fluency and causes financial losses due machine malfunction. Most threatened are components like transmission parts, tools or electronics. The authors as example show case of a damaged transmission gear wheel. Under mechanical stress of these parts can cause a progressive abrasion or damage. In case if the gear wheel is made from brittle material, there is much higher risk of damage. Our example of modern RE techniques application shows transmission gear wheel made from plastic material. This was irretrievably damaged under machine running (Figure 4.1.). As it came to snap of part of wheel it doesn’t allow another machine running. Damaged gear wheel like this should be changed for a new one.

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Figure 4.1. Damaged component – gear-wheel [65].

To eliminate machine failure due part damage, the authors decided to apply reverse engineering. The damaged part was 3D scanned and aroused point´s cloud was getting into CAD part. A missing part of the gear wheel had to be added in CAD, and finally a new gear wheel was created using rapid prototyping [65].
The authors argue that these techniques can be used to:

- Understand the design and operation of mechanical systems: Reverse engineering can be used to create a digital 3D model of an existing mechanical system. This model can then be used to analyze the design and operation of the system, identify potential problems, and develop repair plans.
- Improve service processes: Reverse engineering techniques can be used to create digital service instructions and procedures. These instructions can then be used by service technicians to service mechanical systems faster and more efficiently.
- Design new mechanical systems: Reverse engineering techniques can be used to analyze existing mechanical systems and identify their shortcomings. This information can then be used to design new mechanical systems that are more efficient, reliable, and easier to service.

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The authors present several examples of the use of reverse engineering techniques in the servicing of mechanical systems. For example, reverse engineering has been used to [65]:

- Reconstruct a damaged turbine rotor: A digital 3D model of the rotor was created using laser scanning. This model was then used to analyze the cause of the failure and design a new rotor.

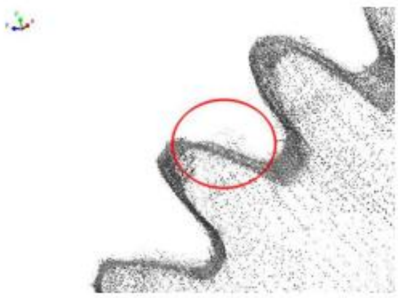

Figure 4.2. Model of 3D scanning with inaccuracy [65]

- Improve the service process of a gearbox: Digital service instructions were created for a gearbox. These instructions included detailed information on the disassembly, assembly, and repair of the gearbox.
- Design a new brake system: Existing brake systems were analyzed using reverse engineering techniques. This information was then used to design a new brake system that was more efficient and easier to service.

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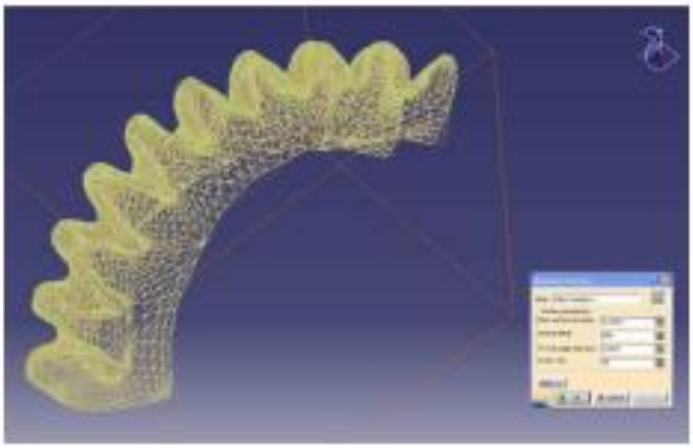

Figure 4.3. Mesh of a gear wheel part [65].

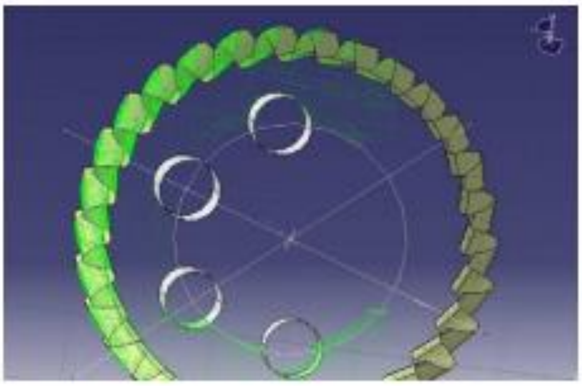

Figure 4.4. Base geometry of gear wheel [65]

- The authors conclude that reverse engineering techniques can be a valuable tool for companies that service mechanical systems. These techniques can help companies to better understand the design and operation of mechanical systems, improve service processes, and design new mechanical systems.

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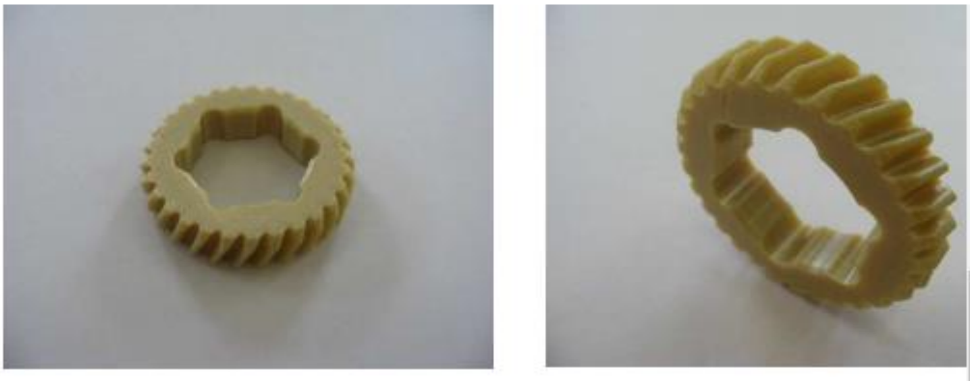

Figure 4.5. New gear wheel made from ULTEM 9085 [65]

4.2 *Applications in Medical Life Sciences*

Reverse engineering plays a crucial role in various aspects of medical life sciences, offering significant benefits for:

1. Medical device development and improvement :
   - Understanding existing device design and functionality: Reverse engineering can be used to analyze existing medical devices, creating 3D models for further investigation. This allows for a deeper understanding of their design principles, material properties, and potential limitations.[66]
   - Developing new and improved medical devices: By studying existing devices, engineers can identify areas for improvement and develop new devices with enhanced features, functionalities, or safety protocols. This can lead to more efficient, effective, and accessible medical treatments.[67]
   - Creating patient-specific implants and prosthetics: Advanced techniques like 3D printing and reverse engineering can be combined to create customized implants and prosthetics that perfectly fit individual patients' needs, improving treatment outcomes and patient comfort.[68]

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2. Analyzing and researching biological structures:
    - Reconstructing complex biological structures: Reverse engineering can be used to analyze and reconstruct 3D models of intricate biological structures like organs, tissues, and bones. This facilitates medical research and training by providing accurate and detailed visualizations.[69]
    - Developing biocompatible materials: By understanding the structure and properties of natural tissues, researchers can design and develop biocompatible materials that are readily accepted by the human body. This advancements are crucial for applications like implants, prosthetics, and drug delivery systems.[70]

3. Drug delivery and pharmaceutical research:
    - Understanding drug delivery mechanisms: Reverse engineering can analyze existing drug delivery systems, revealing insights into their release mechanisms, effectiveness, and potential targeting methods. This knowledge helps in developing improved drug delivery systems with targeted drug release and reduced side effects.[71]
    - Drug discovery and development: Studying the structure and function of biological targets like proteins and enzymes can be facilitated by reverse engineering techniques. This knowledge helps in designing and developing new drugs that specifically target these biological targets, leading to more effective treatments.[72]

4. Medical device repair and maintenance:
    - Understanding device functionality for repairs: When medical devices malfunction, reverse engineering can help technicians understand their internal structure and functionality, facilitating efficient repairs and maintenance. This can potentially extend the lifespan of crucial medical equipment and reduce overall healthcare costs.[73]

5. Forensic medicine and education:

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- Analyzing and reconstructing fractured bones: In forensic medicine, reverse engineering can analyze fractured bones to help reconstruct the events leading to the injury. This information can be crucial for legal investigations and accident reconstruction.[74]
- Creating educational and training materials: By studying the structure and function of medical devices and biological systems through reverse engineering, valuable insights can be gained for creating educational and training materials for medical professionals.[75]
- Overall, reverse engineering offers a valuable set of tools and techniques for various applications in medical life sciences, contributing to advancements in medical device development, biological research, drug discovery, and healthcare delivery.[75]

4.3 *Applications in Software Industries*

Reverse engineering plays a crucial role in various aspects of the software industry, offering benefits in several areas:

1. Recovering Lost or Corrupted Data: When software encounters crashes or malfunctions, data loss or corruption can occur. Reverse engineering can be used to analyze the software's structure and functionality, potentially enabling the recovery of lost or corrupted data. [78]

2. Understanding Legacy Code and Systems: Many software projects involve maintaining and updating older codebases (legacy systems).[79] Reverse engineering helps developers understand the architecture, logic, and data flow within these systems, facilitating maintenance, debugging, and modernization efforts.[80]

3. Identifying Security Vulnerabilities: By analyzing the software's code and underlying functionalities, reverse engineering can help identify potential security vulnerabilities and

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weaknesses.[81] This allows developers to proactively address these issues and enhance the software's security posture.

4. Creating Compatible Software with Existing Systems: When developing new software, it's often essential to ensure compatibility with existing systems.[82] Reverse engineering can be used to understand the communication protocols and data formats used by existing systems, enabling the creation of compatible software that interacts seamlessly with them.

5. Migrating Software to New Platforms or Technologies: As technology evolves, migrating software to new platforms or technologies might become necessary. [83] Reverse engineering assists in understanding the original software's design and functionality, enabling the development of a new version compatible with the target platform or technology.

6. Debugging Complex Software Issues: When encountering complex software bugs or glitches, traditional debugging methods might not suffice.[84] Reverse engineering can provide deeper insights into the software's internal workings, aiding developers in pinpointing the root cause of the issue and implementing effective solutions.

7. Improving Software Performance and Efficiency: By analyzing the code structure and execution flow through reverse engineering, developers can identify bottlenecks and inefficiencies within the software. [85] This knowledge allows them to optimize the code and improve the software's overall performance and efficiency.

8. Creating Educational and Training Materials: By studying the design and implementation of existing software through reverse engineering, valuable insights can be gained for creating educational and training materials for developers. [86] This can be particularly beneficial for understanding software architecture, design patterns, and best practices.

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Overall, reverse engineering serves as a versatile tool in the software industry, contributing to various tasks, from data recovery and legacy system maintenance to security analysis, software compatibility, and performance optimization.

4.4 *Applications in Film Entertainment or Animation Industry*

In the film entertainment or animation industry, reverse engineering provides several advantages. It animates objects using reverse-engineered human skeletons, performs 3D scanning for rapid surfacing of scale models, supports online marketing and presentations, and brings real-life forms into the virtual gaming industry. [87]

For example, the movie "Gravity," winner of the 86th Academy Awards, extensively used reverse engineering to create virtual environments, with physical sets limited to the interiors of space capsules and portions of the ISS space station.

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5 Conclusion

Reverse engineering is the practice of replicating an object, artefact, or software that lacks documentation in order to uncover its design, materials, specifications, or functions. The process involves examining a system or component to understand its structural and functional aspects by analyzing detailed CAD data. This process typically begins with digital measurements of the component using optical scanners (non-contact) or CMMs (contact), followed by creating a 3D model from the obtained point data using CAD/CAM/CAE or similar software.

Reverse engineering proves highly effective in situations where design modifications are needed for a product lacking its original CAD model. It also plays a crucial role in inspecting complex shapes for wear, which would otherwise be challenging, time-consuming, and costly to do manually. Additionally, it enables competitive benchmarking by revealing insights into competitors' product design secrets.

In the medical industry, reverse engineering is invaluable for simulating the results of artificial implants before their actual implementation in the human body. This process not only saves time and money but can also be life-saving. Therefore, the primary objective of reverse engineering is to reduce lead times, consequently shortening manufacturing cycles.

As businesses strive to overcome time constraints and innovate products in today's competitive market, reverse engineering approaches are gaining popularity. However, there is still room for improvement in these methods, particularly in terms of efficiency and accuracy. Many reverse engineering algorithms require further refinement to minimize errors and enhance results. By continually refining reverse engineering processes, we can produce higher-quality products and expand the scope of its applications in the future.

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