Springer Series in Advanced Manufacturing

Series Editor

Professor D.T. Pham
Manufacturing Engineering Centre
Cardiff University
Queen's Building
Newport Road
Cardiff CF24 3AA
UK

Other titles in this series

Assembly Line Design
B. Rekiek and A. Delchambre

Advances in Design
H.A. ElMaraghy and W.H. ElMaraghy (Eds.)

Effective Resource Management in Manufacturing Systems: Optimization Algorithms in Production Planning
M. Caramia and P. Dell'Olmo

Condition Monitoring and Control for Intelligent Manufacturing
L. Wang and R.X. Gao (Eds.)

Optimal Production Planning for PCB Assembly
W. Ho and P. Ji

Trends in Supply Chain Design and Management: Technologies and Methodologies
H. Jung, F.F. Chen and B. Jeong (Eds.)

Process Planning and Scheduling for Distributed Manufacturing
L. Wang and W. Shen (Eds.)

Collaborative Product Design and Manufacturing Methodologies and Applications
W.D. Li, S.K. Ong, A.Y.C. Nee and C. McMahon (Eds.)

Decision Making in the Manufacturing Environment
R. Venkata Rao

Vinesh Raja and Kiran J. Fernandes (Eds.)

Reverse Engineering

An Industrial Perspective

Springer

Vinesh Raja, PhD, C.Eng
Warwick Manufacturing Group
University of Warwick
Coventry
UK

Kiran J. Fernandes, PhD, C.Eng
The York Management School
University of York
Heslington
York
UK

British Library Cataloguing in Publication Data
Reverse engineering : an industrial perspective. -
(Springer series in advanced manufacturing)
1. Reverse engineering
I. Raja, Vinesh II. Fernandes, Kiran J.
620'.0042'0285
ISBN-13: 9781846288555

Library of Congress Control Number: 2007934757

Springer Series in Advanced Manufacturing ISSN 1860-5168
ISBN 978-1-84628-855-5 e-ISBN 978-1-84628-856-2

Printed on acid-free paper

© Springer-Verlag London Limited 2008

Apart from any fair dealing for the purposes of research or private study, or criticism or review, as permitted under the Copyright, Designs and Patents Act 1988, this publication may only be reproduced, stored or transmitted, in any form or by any means, with the prior permission in writing of the publishers, or in the case of reprographic reproduction in accordance with the terms of licences issued by the Copyright Licensing Agency. Enquiries concerning reproduction outside those terms should be sent to the publishers.

The use of registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant laws and regulations and therefore free for general use.

The publisher makes no representation, express or implied, with regard to the accuracy of the information contained in this book and cannot accept any legal responsibility or liability for any errors or omissions that may be made.

9 8 7 6 5 4 3 2 1

Springer Science+Business Media
springer.com

About the Editors

Prof. Vinesh Raja is a Professorial Fellow in Informatics at the University of Warwick. He is incharge of the Informatics Group, which encompasses the Virtual Reality Center (VRC) and the Collaborative Product Commerce Center (CPC) at the Warwick Manufacturing Group. He focuses on augmenting and extending everyday learning and work activities with interactive technologies that move 'beyond the desktop'. This involves designing enhanced user experiences through appropriating and assembling a diversity of technologies including haptics, handheld and pervasive computing. The main focus of his research is not the technology per se but the design and integration of the digital representations that are presented *via* them to support social and cognitive activities in ways that extend current capabilities.

Dr. Kiran Jude Fernandes is the 40th Anniversary Research Lecturer in Management at the University of York. He has been a pioneer in the systematic study of information modeling techniques and tools and has studied their evolution using techniques from the biological sciences. His research and teaching interests include strategic uses of information systems, information management, and the impact of information technology on the risks and benefits of outsourcing and strategic alliances. Before joining the University of York, Kiran worked at the University of Warwick and the NASA John C. Stennis Space Center.

Preface

Congratulations and thank you for reading this book! You hold in your hand perhaps the first book solely written on mechanical reverse engineering from an industry perspective. The motivation for this book originates from the needs of today's global industry.

We recall an incident during one of our industrial trips to a local manufacturing company. The office secretary was photocopying documents for this meeting, when the manufacturing manager remarked, "Wouldn't it be nice if I could do the same with mechanical parts, it would save me and my team a lot of time and money." "Have you not heard of reverse engineering?" we asked him. "Reverse engineering, isn't that something to do with programming computers?" "No," we replied. "Reverse engineering (RE) refers to creating a computer-aided design (CAD) model from an existing physical object, which can be used as a design tool for producing a copy of an object, extracting the design concept of an existing model, or reengineering an existing part." His eyes lit up. Such situations are not uncommon in today's manufacturing arena.

With globalization and trade liberalization, manufacturing companies face increasing competition from goods and services produced in lower wage economies. Countries in the West cannot compete against low wages and must therefore depend on raising innovation and best practices to create better products. In an attempt to compete in such a volatile environment, companies are looking to lean and agile strategies to compete and survive. Lean or world class manufacturing is principally aimed at reducing waste and controlling things that can be measured and controlled. On the other hand, agility deals with things that cannot be controlled.

To be agile and lean, companies cannot apply traditional approaches that often result in problems with inventories, overhead, and inefficiencies. Companies need to create small quantities of highly customized, designed-to-order parts that meet the needs of the global customer. The swift trend toward a multiplicity of finished products with short development and production lead times has led many companies into problems with inventories, overhead, and inefficiencies. They are trying to apply the traditional mass-production approach without realizing that the whole environment has changed. Mass production does not apply to products where the customers require small quantities of highly custom, designed-to-order products, and where additional services and value-added benefits such as product upgrades and future reconfigurations are as important as the product itself. Approaches such as rapid prototyping (RP) and reverse engineering (RE) are helping to solve some of these problems.

Rapid Prototyping – Rapid prototyping is a relatively new class of technology used for building physical models and prototype parts from 3-D computer-aided design (CAD) data. Unlike milling machines (which are subtractive), RP systems join liquid, powder, and sheet materials together to form complex parts. Layer-by-layer, RP machines fabricate plastic, wood, ceramic, and metal objects based on thin horizontal cross sections taken from computer models.

Reverse Engineering – Reverse engineering encompasses a variety of approaches to reproduce a physical object with the aid of drawings, documentation, or computer model data. In the broadest sense, reverse engineering is whatever it takes–manual or under computer control–to reproduce something.

This is a book for people interested in RE from an industrial perspective. Several journal papers have discussed issues related to RE, but from our conversations with industrialists and our personal experience, there is a huge gap in practical literature in this field, especially in manufacturing. Hence, this book is written for the benefit of the industrialist, who might not have the time to "scramble" through libraries and other sources to read journal papers. Although this book is written for such "novice" engineers, we expect the reader to be familiar with basic computer-aided design and manufacturing principles. The main theme of the book is to get you started using RE as quickly as possible. We have provided examples from the aerospace, automotive, and medical equipment industries to familiarize you with the principles and techniques of reverse engineering.

Probably the most unusual thing about this book is that we start with practical examples from industry. This approach has worked well in the classroom when we teach our course to industrial students. We expect the same results with this book. Many of the examples used in the later chapters depend on the principles and techniques of RE, so, it is essential that you read the first few chapters.

Having taught reverse engineering to industrial managers and engineers for a number of years, we are beginning to see that RE is finally receiving the respect it deserves.

Acknowledgments

We extend our sincere thanks to Professor Lord Kumar Bhattacharyya and our colleagues at the Warwick Manufacturing Group, where we spent most of our time researching and actively debating this topic, and to all of our industrial partners and friends who actively assisted us with their valuable contributions.

Our particular thanks to all the authors without whom this book would not have been possible.

The editors wish to thank the EU FP6 Network of Excellence for Innovative Production Machines and Systems (I*PROMS) for partly financing the preparation of this book.

Special thanks to our family members, who put up with our late night editing sessions for so long and finally thanks to all the staff at Springer, who worked hard in making this book a reality.

Vinesh Haridas Raja
Kiran Jude Fernandes

Contents

List of Contributors

Mongi Abidi
University of Tennessee
Department of Electrical and Computer Engineering
Imaging, Robotics, and Intelligent Systems Lab
330 Ferris Hall, Knoxville TN 37996
USA

Brian C. Beherens
Department of Decision Sciences and MIS Saint Louis University
Cook School of Business
3674 Lindell Blvd.
Saint Louis, MO 63108
USA

Frits Feenstra
TNO Science and Industry,
P.O. Box 6235
5600 HE, Eindhoven
Netherlands
e-mail: f.feenstra@ind.tno.nl

Kiran Jude Fernandes
Department of Management Studies
University of York
Heslington, York YO10 5DD
UK
e-mail: kf501@york.ac.uk

Ping Fu
Geomagic
3200 East Hwy 54
Cape Fear Building, Suite 300
Research Triangle Park
NC, 27709
USA
e-mail: pfu@geomagic.com

L.C. Hieu
Manufacturing Engineering Centre
Cardiff University
Queen's Building, Newport Road
Cardiff CF24 3AA
UK

John Keast
Warwick Manufacturing Group
International Manufacturing Centre
University of Warwick
Coventry, CV4 7AL
UK
e-mail: J.E.Keast@warwick.ac.uk

Andreas Koschan
University of Tennessee
Department of Electrical and Computer Engineering
Imaging, Robotics, and Intelligent Systems Lab
330 Ferris Hall, Knoxville TN 37996
USA
e-mail: akoschan@utk.edu

Reuven R. Levary
Department of Decision Sciences
and MIS Saint Louis University
Cook School of Business
3674 Lindell Blvd.
Saint Louis, MO 63108
USA
e-mail: levarypr@slu.edu

H.T. Loh
Department of Mechanical
Engineering
National University of Singapore
21 Lower Kent Ridge Road
Singapore 119077

Eef Moeskops
TNO Science and Industry
P.O. Box 6235
5600 HE, Eindhoven
Netherlands

David Page
University of Tennessee
Department of Electrical and
Computer Engineering
Imaging, Robotics, and Intelligent
Systems Lab
330 Ferris Hall, Knoxville TN 37996
USA

D.T. Pham
Manufacturing Engineering Centre
Cardiff University
Queen's Building, Newport Road
Cardiff CF24 3AA
UK
e-mail: phamdt@cardiff.ac.uk

Vinesh Raja
Warwick Manufacturing Group
International Manufacturing Centre
University of Warwick
Coventry, CV4 7AL
UK
e-mail: vinesh.raja@warwick.ac.uk

Y.S. Wong
Department of Mechanical
Engineering
National University of Singapore
21 Lower Kent Ridge Road
Singapore 119077

Y.F. Zhang
Department of Mechanical
Engineering
National University of Singapore
21 Lower Kent Ridge Road
Singapore 119077
e-mail: mpezyf@nus.edu.sg

Chapter 1

Introduction to Reverse Engineering

Vinesh Raja, University of Warwick, UK

Abstract

This chapter introduces readers to the term reverse engineering (RE), and to the associated techniques that can be used for scanning physical parts. In addition, the chapter presents the process of reverse engineering and the strategy for scanning and converting the scanned data into a 3-D surface or solid model.

1.1 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

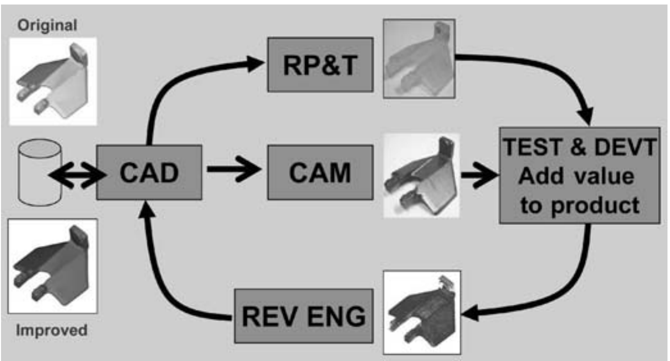

Figure 1.1. Product development cycle

in CADCAM, 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".

1.2 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 and reverse engineering. Forward engineering 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 existing part, subassembly, or product, without drawings, documentation, or a computer model is known as reverse engineering. 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 (Motavalli & Shamsaasef 1996). Abella *et al.* (1994) 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 *et al.*(1993) 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 jewelry design and reproduction For example, when a new car is launched on the market, competing manufacturers may buy one and disassemble it to learn how it was built and how it works. In software engineering, good source code is often a variation of other good source 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 1.2. 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

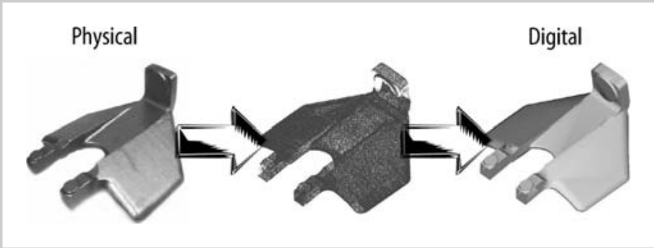

Figure 1.2. Physical-to-digital process

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.

1.3 Why Use Reverse Engineering?

Following are some of the reasons for using reverse engineering:

- The original manufacturer no longer exists, but a customer needs the product, *e.g.*, aircraft spares required typically after an aircraft has been in service for 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 anthropometry of a population.

- 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.

1.4 Reverse Engineering–The Generic Process

The generic process of reverse engineering is a three-phase process as depicted in Figure 1.3. The three phases are scanning, point processing, and application-specific geometric model development. Reverse engineering strategy must consider the following:

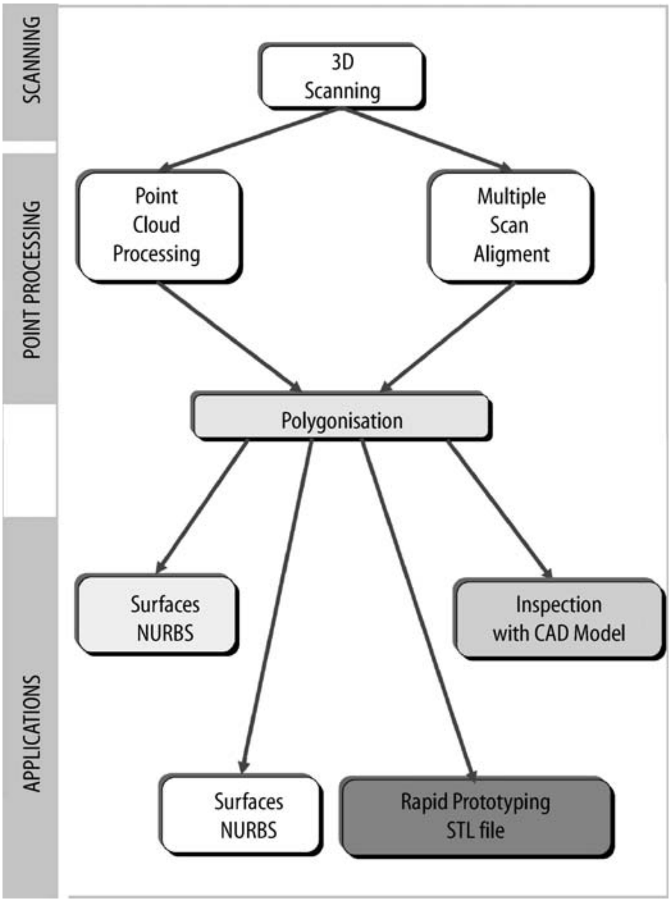

Figure 1.3. Reverse engineering – the generic process

- 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

1.5 Phase 1–Scanning

This phase is involved with the scanning strategy–selecting the correct scanning technique, preparing the part to be scanned, and performing the actual scanning 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-ons to the existing computer numerically controlled (CNC) machine tools. There are two distinct types of scanners, contact and noncontact.

1.5.1 Contact Scanners

These devices employ contact probes that automatically follow the contours of a physical surface (Figure 1.4). In Ithe current marketplace, contact probe

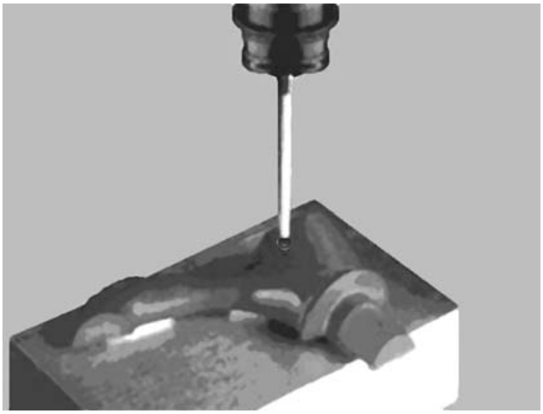

Figure 1.4. Contact scanning touch probe. Originally published in *Rapid Prototyping Casebook*, McDonald, J.A., Ryal, C.J. and Wimpenny, D.I., 2001, © John Wiley and Sons Limited. Reproduced with permission.

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.

1.5.2 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 1.5. 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.
- Some noncontact systems have problems generating data describing surfaces, which are parallel to the axis of the laser (Figure 1.6).
- 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.

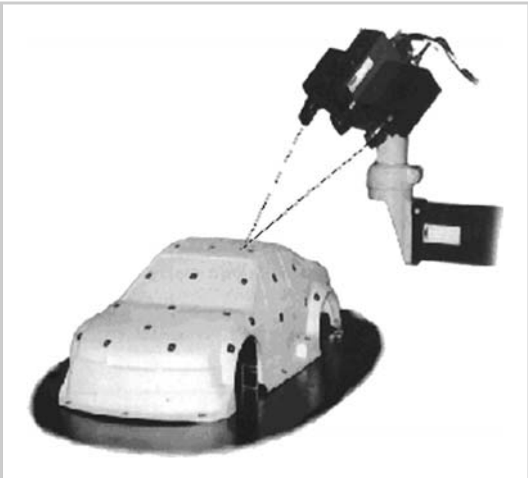

Figure 1.5. Optical scanning device. Originally published in *Rapid Prototyping Casebook*, McDonald, J.A., Ryal, C.J. and Wimpenny, D.I., 2001, © John Wiley and Sons Limited. Reproduced with permission.

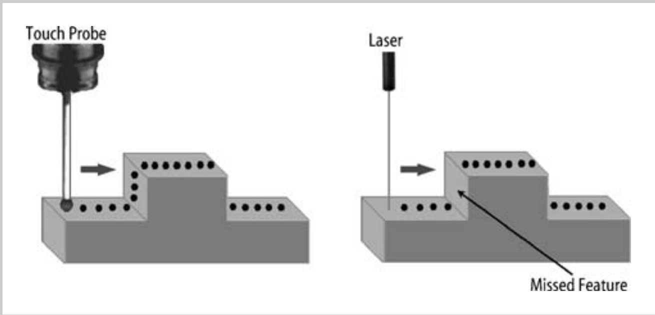

Figure 1.6. Vertical faces–touch probe versus a laser. Originally published in *Rapid Prototyping Casebook*, McDonald, J.A., Ryal, C.J. and Wimpenny, D.I., 2001, © John Wiley and Sons Limited. Reproduced with permission.

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).

1.6 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 performed 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. This phase also allows us to merge multiple scan data sets. 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.

1.7 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 arise frequently throughout any product introduction process.

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 designed to display and process large amounts of point data; as a result new RE modules 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.

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 designed 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.

Chapter 2 builds on Chapter 1 by providing an in-depth depiction of methodologies and techniques for reverse engineering.

Chapter 3 presents information on reverse engineering hardware and software and also provides excellent information on commercially available reverse engineering hardware and software.

Chapter 4 provides a structured approach for selecting the appropriate reverse engineering system for a specific business need.

Chapter 5 introduces the fundamentals of rapid prototyping with an in-depth description of various commercially available rapid prototyping technologies.

Chapter 6 provides excellent information on the relationship between reverse engineering and rapid prototyping.

Chapter 7 provides cases studies of successful applications of reverse engineering in the automotive industry.

Chapter 8 provides cases studies of successful applications of reverse engineering in the aerospace industry.

Chapter 9 provides cases studies of successful applications of reverse engineering in the medical equipment industry.

Chapter 10 describes the legal aspects and implications of reverse engineering.

Chapter 11 discusses the barriers to adopting reverse engineering.

Chapter 2

Methodologies and Techniques for Reverse Engineering–The Potential for Automation with 3-D Laser Scanners

David Page, Andreas Koschan, and Mongi Abidi, University of Tennessee, USA

Abstract

In this chapter, we present methodologies and technologies for automating reverse engineering (RE) through digital imaging and computer vision. We begin this chapter with a definition of RE in terms of generating computer-aided design (CAD) models from existing objects and components. We use the term computer-aided reverse engineering (CARE) to describe this process. With this definition, we present a brief overview of the traditional approach to RE using coordinate measuring machines (CMMs). Then, we begin the main focus of the chapter where we explore digital imaging and computer vision as an alternative to CMMs. This exploration begins with data acquisition, where we present laser-based range scanners as a promising approach. For these scanners, we explain and highlight differences in data resolution and scanning rates and contrast those to CMM performance. Next, we present a processing pipeline for creating CAD models using these scanners. This processing includes tasks such as view registration, surface integration, patch reconstruction, model fitting, noise removal, and other functions. This chapter explains these topics to help the reader understand their importance in designing an RE imaging system and the impact that various parameters have on modeling accuracy.

2.1 Computer-aided Reverse Engineering

Reverse engineering (RE) has many meanings to many different people. As we begin this chapter, we first focus our attention on the specific meaning that we intend to address and then extend our attention to the automation of RE, which we call computer-aided reverse engineering (CARE). To this end, this chapter discusses CARE in general and then explores 3-D laser scanning in depth as an emerging CARE technology from the computer vision community, as introduced in Varady *et al.* (1997), Bernardini *et al.* (1999), and Page *et al.* (2003). The chapter details the methodologies and techniques associated with computer vision scanning and notes specific challenges for the CARE problem.

2.1.1 What Is Not 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 high-level 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).

2.1.2 What is Computer-aided (Forward) Engineering?

In the late 1970s and into the 1980s, computer-aided design (CAD)–a component 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 emergence 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 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