VTT PUBLICATIONS 298

CAD model-based planning and vision guidance for optical 3D co-ordinate measurement

Heikki Ailisto

VTT Electronics

Dissertation for the degree of Doctor of Technology
to be presented, with the permission of the Department of Electrical Engineering
of the University of Oulu, for public discussion in Auditorium L10, Linnanmaa,
on March 14th, 1996, at 12 noon.

TECNICAL RESEARCH CENTRE OF FINLAND
ESPOO 1997

ISBN 951-38-4956-2
ISSN 1235-0621

JULKAISIJA – UTGIVARE – PUBLISHER

Valtion teknillinen tutkimuskeskus (VTT), Vuorimiehentie 5, PL 42, 02151 ESPOO
puh. vaihde (09) 4561, faksi 456 4374

Statens tekniska forskningscentral (VTT), Bergsmansvägen 5, PB 42, 02151 ESBO
tel. växel (09) 4561, fax (09) 456 4374

Technical Research Centre of Finland (VTT), Vuorimiehentie 5, P.O.Box 42, FIN–02151 ESPOO, Finland
phone internat. + 358 9 4561, telefax + 358 9 456 4374

VTT Elektroniikka, Optoelektroniikka, Kaitoväylä 1, PL 1100, 90571 OULU
puh. vaihde (08) 509 111, faksi (08) 551 2320

VTT Elektronik, Optoelektronik, Kaitoväylä 1, PB 1100, 90571 ULEÅBORG
tel. växel (08) 509 111, fax (08) 551 2320

VTT Electronics, Optoelectronics, Kaitoväylä 1, P.O.Box 1100, FIN–90571 OULU, Finland
phone internat. + 358 8 509 111, fax + 358 8 551 2320

Technical editing Leena Ukskoski

VTT OFFSETPAINO, ESPOO 1997

Dedicated to my sons Iivari, Jussi, Matti and Mikko

Ailisto, Heikki. CAD model-based planning and vision guidance for optical 3D co-ordinate measurement. Espoo 1997. Technical Research Centre of Finland, VTT Publications 298. 70 p. + app. 63 p.

UDC 535.321:681.3
Keywords geometric control, measurement, planning, three dimensional systems, CAD, models, accuracy, machine vision, lasers, optical measurement, inspection

ABSTRACT

Controlling the geometric accuracy of manufactured products is seen as an important issue, since it affects both production costs and quality. Optical measurement technology has been found suitable for various geometric control applications, and laser rangefinder devices in particular are now being used to measure large objects and structures.

This thesis describes the development of a concept of CAD model-based automated 3D measurement and the evaluation of its feasibility in cases drawn from industrial needs. Automated 3D measurement can be seen as comprising two steps: measurement planning and measurement execution. Measurement planning takes place interactively using the information contained in the CAD model of the object, to yield a measurement plan in a form readable by the measurement system. In the second step, the planned measurement sequence is executed automatically under computer control using sensory feedback. The analysis and use of the results, e.g. for quality control or for guiding parts assembly, which is naturally the following step, is touched on only briefly in this work.

The concept was evaluated by implementing a graphical measurement planning tool and two automatic measurement systems. The tool was built using the development environment of a commercial CAD package, which ensured compatibility with existing CAD data. The experimental automatic measurement systems were based on optical co-ordinate measuring devices and were equipped with vision systems for sensory feedback. The operation chain from CAD model-based measurement planning to comparison between the measured and designed geometries was demonstrated. Successful experiments with automatic operation controlled by the measurement plan and vision guidance were carried out and the key performance criteria were met.

PREFACE

This thesis is based on the author's research work on CAD model-based automated 3D measurement carried out during the years 1989 - 1996 as part of a more extensive research effort conducted by VTT Electronics, the University of Oulu and industrial companies concerning laser rangefinding technology and its applications. The major part of the work was done in the "3D2000" project in 1993 - 96. The project was conducted in a good spirit of teamwork by researchers and engineers at VTT Electronics, Helsinki University of Technology, the University of Oulu, Mapvision Oy, Prometrics Oy and Spectra-Physics VisionTech Oy, and I am proud and happy to have been responsible for the project.

I would like to thank Prof. Matti Pietikäinen of the University of Oulu for his guidance and encouragement during my studies, and Dr. Jorma Lammasniemi, who encouraged me to pursue this work. Special thanks are due to Dr. Ilkka Moring, whose dissertation set an example for me and whose advice and support have been of great value. I also wish to thank Dr. Markku Manninen for many ideas and visions which he kindly shared with me during our decade of co-operation. Mr. Jussi Paakkari made it possible to write this thesis by standing in for me in my everyday duties at VTT.

I wish to express my gratitude to my co-workers at VTT Electronics and other research institutes and companies who participated in the 3D2000 project. Special thanks are due to Mr. Risto Mitikka, Mr. Hannu Kallio-Kokko, Mr. Ilkka Kaisto and Mr. Hannu Jokinen, whose experience and commitment made it all possible.

Professors Henrik Haggrén and Risto Myllylä deserve thanks for the time that they devoted to reviewing and commenting on this thesis. Ms. Tuija Soininen is acknowledged for finalising the drawings and Professor Harri Kopola for commenting on the draft version.

The Technology Development Centre of Finland, VTT, and the above-mentioned companies are acknowledged for the support they have given to the research projects on which this dissertation is based. VTT and the Foundation for Technology in Finland provided the financial support that enabled me to finish this thesis.

Finally, I must take this opportunity to thank my friends at Näyhä's table, who have made it such fun to work at VTT. The practise gained in debates concerning numerous topics from child upbringing to long distance running and the history of the former Soviet Union will, I hope, help me to defend this thesis.

Oulu, January 1997

Heikki Ailisto

CONTENTS

ABSTRACT 5
PREFACE 6
LIST OF PUBLICATIONS 8
LIST OF SYMBOLS AND ABBREVIATIONS 10
1 INTRODUCTION 11
1.1 Motivation 11
1.2 Scope of the thesis 13
1.3 Contribution of the thesis 14
1.4 Summary of the publications 15
2 RELATED WORK ON CAD-BASED MEASUREMENT PLANNING AND AUTOMATED OPTICAL 3D MEASUREMENT 19
2.1 Introduction 19
2.2 CAD-based measurement planning systems 21
2.2.1 Planning systems independent of measurement technology 22
2.2.2 Planning systems for optical inspection 23
2.2.3 Planning systems for CMMs 24
2.3 Automated optical 3D measurement systems 26
2.3.1 Theodolite-based systems 26
2.3.2 Machine vision based systems 29
2.4 Discussion 30
3 THE CONCEPT OF CAD MODEL-BASED AUTOMATED 3D MEASUREMENT 35
3.1 CAD model-based measurement planning 36
3.2 Automatic measurement execution 39
3.3 Discussion 40
4 EXPERIMENTATION 43
4.1 Measurement planning tool 43
4.1.1 Implementation of the measurement planning tool 44
4.1.2 Experiments 46
4.2 Vision-guided optical co-ordinate meters 49
4.2.1 Implementation of vision guidance 50
4.2.2 Experimental results 53
4.3 Demonstration cases 54
5 DISCUSSION 57
6 SUMMARY 61
REFERENCES 63
APPENDICES

Appendices of this publication are not included in the PDF version.
Please order the printed version to get the complete publication
(http://www.inf.vtt.fi/pdf/publications/1997/)

LIST OF PUBLICATIONS

The thesis consists of this report and the following seven original publications (Appendices I - VII), which are referred to in the text by their Roman numerals.

I Ailisto, H. 1989. Use of design data in 3D vision-based inspection. In: Pietikäinen, M. & Röning, J. (eds.). SCIA '89. Proceedings of the 6th Scandinavian Conference on Image Analysis, Oulu, Finland, 19 - 22 June 1989. Pattern Recognition Society of Finland. Pp. 467 - 472. ISBN 952-90089-0-2.

II Paakkari, J., Smit, R. & Ailisto, H. 1991. Computer aided measurement planning for 3-D Machine vision. In: Johansen, P. & Olsen, S. (eds.). SCIA '91. Proceedings of the 7th Scandinavian Conference on Image Analysis, Aalborg, Denmark. 13 - 16 August, 1991. Pattern Recognition Society of Denmark. Pp. 807 - 814. ISBN 87-983795-1-8.

III Manninen, M., Torvikoski, T., Kaisto, I., Ailisto, H. & Moring, I. 1992. Acmeter Prog - A new method and system for shape control. In: Pietikäinen, M. & Seppänen, T. (eds.). Proceedings of the 2nd Nordic Workshop on Industrial Machine Vision, Kuusamo, Finland, 29 - 31 March, 1992. Pattern Recognition Society of Finland. 7 p. ISBN 951-42-3316-6.

IV Ailisto, H. & Manninen, M. 1994. Advanced 3D Dimensional Control (D/C) Technology for New Ship Production. In: Nav 94. Proceedings International Conference on Ship and Marine Research. Rome, Italy, 5 - 7 October 1994. Associazione Italiana di Tecnica Navale. Vol. 2, Session VI. 10 p.

V Ailisto, H., Mitikka, R., Moring, I., Jokinen, H. & Kaisto, I. 1996. 3D measurement controlled by a CAD model-based measurement planning and vision system. International Journal of Pattern Recognition and Artificial Intelligence, vol. 10, no. 2, pp. 151 - 164. ISSN 0218-0014.

VI Ailisto, H., Mitikka, R., Moring, I. & Kaisto, I. 1995. Optical three-dimensional coordinate meter with vision guidance for submillimeter pointing to tags. Optical Engineering, vol. 34, no. 9, pp. 2603 - 2610. ISSN 0091-3286.

VII Ailisto, H., Mitikka, R., Moring, I. & Jokinen, H. 1995. Vision guidance of laser profiler for monitoring refractory lining wear in steel mills. In: El-

Hakim, S. (ed.). Videometrics IV. Proc. SPIE 2598. Philadelphia, 25 - 26 October 1995. SPIE. Pp. 245 - 254. ISBN 0-8194-1962-1.

Paper I introduces the idea of using CAD data on the object to be measured and a limited set of measurement functions to plan the inspection task. Paper II describes an experimental implementation of this idea, in which the author was responsible for the design and implementation of the experimental system and took part in implementation and testing.

Paper III describes an advanced commercial 3D measurement system relying on the concept of preplanned measurement of selected points or shape profiles. The author took part in planning the system concept. Paper IV is an overview of dimensional control based on optical co-ordinate measurement in shipyard applications. The author took part in developing the optical co-ordinate meter-based dimensional control applications and was responsible for the development of the new approach presented.

Papers V - VII elaborate the concept of CAD model-based automated 3D measurement and describe experimental systems implemented for its evaluation. Paper V describes the experimental system with CAD model-based measurement planning and vision-guided measurement. Paper VI presents a vision-guided optical co-ordinate meter based on the system described in Paper III and reports on its performance. Paper VII describes a laser profiler equipped with a vision system and modified control software to improve its operative and performance characteristics in monitoring refractory lining wear in steel mills. The author led the research work described in these papers and took part in the implementation and experimentation.

The author was the sole writer of Paper I. He wrote Papers II and IV together with co-authors and participated in the polishing of Paper III. Papers V, VI and VII were written by the author, the co-authors commenting on them during their preparation.

LIST OF SYMBOLS AND ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
AAR	Angle-Angle-Range
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CCD	Charge Coupled Device
CIM	Computer Integrated Manufacturing
CMM	Co-ordinate Measuring Machine
DMIS	Dimensional Measuring Interface Specification
DXF	Data eXchange file Format
FMS	Flexible Manufacturing System
IFC	Inspection Code Fragment
IGES	Initial Graphics Exhange Specification
IVIS	Integrated Volumetric Inspection System
MMD	Measurement Model Data file
MMF	Measurement Model File
PSD	Position-Sensitive Detector
RMS	Root Mean Square
RPDE	Reference Point Distance Error
STEP	STandard fo the Exhange of Product model data
UCS	User Co-ordinate System
VBAT	Vision-Based Automatic Theodolite system
VCM	Vision-based Co-ordinate Measuring system
VMS	Vision Measurement System
VTT	Technical Research Centre of Finland
WCS	World Co-ordinate System

1 INTRODUCTION

1.1 MOTIVATION

Price and quality are the main factors affecting the competitiveness of industrial products, and for this reason industry tends to strive towards lower manufacturing costs while maintaining or improving the quality of the products. Automation has been one of the most important tools in this, as it reduces labour costs and in many cases improves the throughput of the process, thus reducing the amount of money tied up in materials. Automation can improve the quality of the products by reducing the variation in them, i.e. by improving consistency in manufacture.

The geometric accuracy of manufactured objects affects both manufacturing costs and quality. In the shipbuilding industry, for example, reworking due to geometric inaccuracy in parts and sub-assemblies can amount to 20% of the hull construction work (Sormunen 1986). On the other hand, deficiencies in quality, e.g. out-of-tolerance dimensions or shapes, can lead to rejection of products by customers. Control over the geometric accuracy of products is seen as an important issue in the construction of machinery, cars (Kaiser 1985) and ships, for example (Storch & Gribskov 1985, Yuuzaki & Okumato 1992, Manninen & Jaatinen 1992).

Optical measurement methods have been found to be suitable for many geometric accuracy assessment tasks, since they usually involve non-contact and imaging techniques (Cielo 1988). The non-contact nature of such measurements facilitates large stand-offs and measurement volumes, making these techniques especially suitable for the measurement of large objects or structures, e.g. several metres across (Moring 1995). Non-contact measuring principle also facilitates measurements in hostile or inaccessible industrial environments. Another advantage of optical techniques over mechanical probing is measurement speed. The imaging capability of optical measurement methods enables the collection of large amounts of data simultaneously and allows compensation to be made for variable part position and orientation with respect to the sensor.

The 3D co-ordinates of a point with respect to the origin of the co-ordinate system can be determined by measuring two angles and a range. A practical implementation of this idea is a laser radar based angle-angle-range (AAR) device for measuring 3D co-ordinates. This has certain inherent advantages in the measurement of large industrial parts (Moring 1995). It is a direct, monocular device having a resolution which is independent of the measuring distance. These devices have been applied to dimensional control in shipbuilding (Manninen & Jaatinen 1992), measurement of deformation in large structures (Katowski 1992) and the monitoring of fireproof linings in steel manufacturing (Määttä et al. 1993), for example.

Most existing optical 3D measurement devices are either manual, such as theodolites, or are rigidly programmed to perform certain measurement procedures without any sensory feedback[1]. Yet it is clear that certain advantages would be achieved if the measurement devices were equipped with sensory feedback, in the manner of modern industrial robots (Klafter et al. 1989). The advantages achievable with sensory feedback and an associated control method over manual systems include

❑ savings in manpower costs,

❑ possibility for operating in hazardous, unpleasant or unreachable environments,

❑ elimination of human errors caused by fatigue etc.,

❑ improved repeatability of the measurements,

❑ speeding up of the operation.

The advantages gained over rigidly programmed systems include

❑ adaptivity to changes in relative object position and orientation,

❑ adaptivity to changes in actual geometry relative to the design geometry,

❑ possibility for outlier detection in the measurements.

Computer aided design (CAD) has become commonplace in modern industry, so that the dimensions and shape of industrial objects would normally be designed in CAD. Thus geometrical design data are often available on parts and products in the form of CAD files. This has led to the idea of using CAD data as a reference for assessing the geometric accuracy of products (Aubin 1987, Bhanu 1987, Park & Mitchell 1989, Newman & Jain 1995a, Tarbox & Gottschlich 1995).

The benefits of CAD-based inspection and measurement include

❑ ability to use existing CAD files directly as sources of geometric and tolerance information,

❑ interfaces for fast transfer of geometric data in computer-readable format,

❑ possibility for using the graphical user interface of the CAD system in inspection and measurement planning as well, and

❑ possibility for creating methods and procedures for generating measurement programs without user intervention.

CAD model-based optical inspection is still in its infancy, however, and many theoretical and practical problems remain to be solved before it can be adopted for

---

[1] Sensory feedback refers here to the use of additional sensory information to guide the device during execution of the measurements.

industrial use. The experimental systems reported in the literature are based on the concept of generating inspection programs automatically from CAD descriptions, which has led to inflexible solutions applicable to only a limited set of objects.

1.2 SCOPE OF THE THESIS

The goal of this work was to develop a concept for CAD model-based automated 3D measurement and to evaluate its feasibility. The latter was done by implementing the concept and testing it in two cases drawn from the shipbuilding and steelmaking industries.

In particular, we wanted to evaluate

- ❑ the feasibility of CAD model-based measurement planning,
- ❑ the feasibility of executing planned measurement sequences automatically under computer control, and
- ❑ the feasibility of vision-guided optical geometry measurement.

Since laser rangefinders have been found suitable for measuring the geometry of large industrial objects (Määttä et al. 1993, Moring 1995), these devices were used in the feasibility experiments. This does not, however, limit the applicability of the concept to the use of laser rangefinders. In fact, the measurement planning tool developed for the feasibility evaluation has already been used together with a real-time photogrammetry system (Oksanen 1996).

Similarly, the concept of using sensory feedback to guide the measurement process is not limited to vision sensors, although no other sensor modality was considered in the feasibility evaluation performed here. Other possible sources of feedback information include position-sensitive detectors (PSD) (Mäkynen et al. 1994), measurement of the reflected intensity of a rangefinder laser beam, or a separate tracking unit (Kliem 1989).

CAD models are used here as a source of geometrical information in measurement planning in an interactive manner, with no attempts made at fully automated measurement planning or the extraction of data from a CAD model as such. Neither is any attempt made to use data of any other kind than geometrical. The later use of geometrical information acquired with measurement devices is only briefly touched upon in this work and lies beyond its scope. The use of CAD data for the recognition of objects, which is one of the key themes in CAD-based vision (see Bhanu 1987, Hoffman et al. 1989, a collection of selected papers on directions in CAD-based vision in Bowyer 1992, and a related survey by Arman & Aggarwal 1993a), is not considered here.

The approach adopted in this work relies on the same principles as are used in computer aided design, i.e. the computer is seen as a sophisticated tool helping the human to perform the planning task efficiently. This intermediate approach between manual and automatic measurement planning is justified by its ability to combine the best aspects of both methods.

1.3 CONTRIBUTION OF THE THESIS

The main contribution of this thesis is to the development of a concept of CAD model-based automated 3D measurement comprising an interactive CAD data-based measurement planning step and an automated measurement step using sensory feedback. The concept is evaluated and shown to be feasible by developing a research prototype measurement planning tool and two experimental measurement systems and demonstrating them in cases drawn from industrial applications.

The concept of CAD model-based automated 3D measurement is depicted in Figure 1. The first step is measurement planning, which is done interactively with a graphical tool applied to information contained in existing CAD models of the objects to be measured. The CAD model is assumed to provide sufficient geometric information on the objects to facilitate measurement planning. The product of this step is a model containing the information necessary for performing the measurement task itself. The next step is execution of this task in accordance with the information contained in the measurement model and using sensory feedback. This step produces measured co-ordinate values. The results may be used for on-site quality control, guiding of assembly or off-site analysis of manufacturing accuracy or trends.

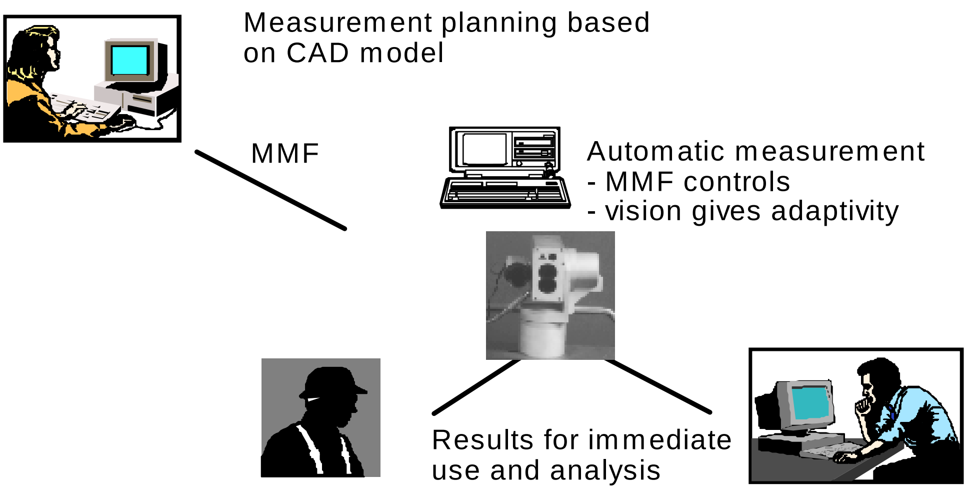

Figure 1. Concept of CAD model-based automated 3D measurement (adapted from Paper IV).

The concept developed here was implemented in order to evaluate its feasibility. A measurement planning tool was designed and implemented using commercial

CAD software as a development environment. Two commercial AAR devices were equipped with control and vision systems facilitating the execution of measurement sequences coded in the Measurement Model File (MMF) and the use of vision guidance. The performance of the experimental systems was evaluated under laboratory conditions and their operation was demonstrated in cases drawn from shipbuilding and steel manufacturing.

The feasibility of the concept was successfully demonstrated throughout the whole operational chain from measurement planning to comparison between the as-measured and as-designed values. The measurement planning tool was used successfully and produced a MMF in the specified format.

The feasibility of proposals regarding MMF controlled operation and sensory feedback was demonstrated and the key performance criteria for vision guidance were met. The vision guidance was of similar accuracy and repeatability to the AAR device that it was guiding or better. Although the speed of the current implementation of vision guidance falls short of the goal, ways of improving it are known to exist.

The ideas and solutions presented in this thesis are continuing to be developed in research organisations and industrial companies. In particular, adaptation of measurement planning tool for photogrammetry applications and the development of vision-guided AAR devices for steel manufacturing applications are still going on.

1.4 SUMMARY OF THE PUBLICATIONS

The remainder of this thesis is organised as follows. Related research into CAD-based measurement planning and work on sensor-guided optical 3D measurement is reviewed in Chapter 2 and the motivation for using CAD data and tools in measurement planning is given. The review of CAD-based measurement planning concentrates on proposed and experimental systems used involving optical measurement technology, although systems relying on co-ordinate measurement machines are briefly touched upon. Automated optical 3D measurement systems are reviewed and arguments are presented for using auxiliary sensors to guide optical co-ordinate measurement with AAR type devices. The concept of CAD model-based automated 3D measurement is elaborated in Chapter 3, and its implementation in experimental cases is described in Chapter 4, together with the results of the feasibility and performance tests. The results and their implications are discussed in Chapter 5, and conclusions are presented in Chapter 6.

This thesis consists of seven publications on CAD-based geometry measurement and inspection. The development of the concept has been an evolutionary process. The idea was first introduced and tentatively tested with data measured with a scanning 3D laser rangefinder, as described in Paper I. An experimental implementation of the idea using a light assembly robot with an optical point range sensor was reported in Paper II, and the next two publications described an advanced 3D measurement system (Paper III) and the application of automated CAD-based measurement to shipbuilding case (Paper IV). Papers V - VII elaborate the concept of CAD model-based automated 3D measurement, describe two experimental systems for evaluating its feasibility and give the results of feasibility and performance analyses.

Paper I introduces the idea of using CAD data on the object to be measured and a limited set of measurement functions to plan the inspection task. The inspection task is divided into an off-line planning step, possibly accomplished concurrently with product design, and an on-line inspection step. The planning step utilises a CAD model of the object to be inspected and tools provided in the CAD system, and results in a device-independent measurement procedure consisting of a limited set of pre-defined measurement functions. A typical inspection sequence would consist of first determining the exact location of the object, i.e., the co-ordinate system set-up, and then performing the planned measurements and comparing the results, typically co-ordinate values or dimensions, with the design values. A tentative experiment with the inspection of a curved steel plate as used in shipbuilding was conducted, the measurement being performed by a scanning laser rangefinder device. Cross-sections extracted from the measured and design data were aligned and then compared numerically and graphically.

Paper II describes an experimental implementation of the idea introduced in Paper I. The system contains the basic elements needed for dimensional inspection, that is a graphical tool for interactive measurement planning, an interpreter to transfer the measurement plans into actions and software to analyse the results. The graphical tool is capable of representing 3D models of polyhedral objects. The measurement plan is generated by saving the co-ordinates and surface normal directions of points chosen by the user with a mouse. An interpreter program reads these data and guides the measurement device, in this case a scara robot with an optical point range sensor, to perform the measurements. The system was able to locate the polyhedral object and measure the dimensions of interest with a repeatability of 0.05 mm and an accuracy of 0.2 mm. The tentative experiments showed the idea of computer aided measurement planning with a graphical software tool and a simple CAD-like model to be feasible, although compatibility with real CAD systems would still be required.

Paper III discusses CAD-based measurement planning in the context of shape control and defines the requirements for a co-ordinate system to be used in measuring large objects and structures, i.e. it must be an intelligent, automatic 3D co-ordinate meter able to execute the measurement programs produced in the planning stage. An optical co-ordinate meter with a capability for finding reference marks is seen as a best alternative, and a system of this kind is designed and constructed. The test results show mm-level accuracy within a measurement range of 2 to 12 m. This system formed the basis for one of the vision-guided experimental systems developed later and described in detail in Paper VI.

Paper IV provided a view of the geometric measurement needs in the shipbuilding application and describes a measurement solution based on AAR devices and design data. Geometric measurements can be used to guide assembly work, dimensional analysis and quality control and to analyse the accuracy of the manufacturing process itself. Two measurement cases, ship block assembly and control of dimensions of curved plates, are discussed. The development of CAD-based measurement planning and an intelligent, vision-controlled co-ordinate measurement is justified in terms of the introduction of automation at shipyards, e.g. in panel lines. The concept of CAD model-based automated 3D measurement is outlined and early results regarding its implementation are presented.

Paper V refines the concept of 3D measurement controlled by CAD model-based measurement planning and vision-guided 3D measurement and describes an experimental implementation. An interactive graphical tool based on a CAD package was designed and implemented for measurement planning. Since the tool is based on a widely used CAD package, it can readily import existing CAD files. The measurement plan produced by the tool is contained in a structured text file named Measurement Model File (MMF), containing the necessary information to control the measurement device, which is described in more detail in Paper VI. The feasibility of the whole concept was tested in a demonstration case in a large hall. Measurements of seven known reference points were planned with the tool and the plan was executed successfully by the measurement device according to the MMF and under vision guidance.

Paper VI describes the experimental 3D measurement device and assess its performance. The device is based on the automatic 3D co-ordinate meter described in Paper III and is equipped with computer vision and new control software working according to the MMFs. The device is capable of locating and pointing to visible features such as circular targets[2] according to instructions in the MMF. The performance of the system with respect to reliability, repeatability, accuracy and speed was assessed in the large hall as mentioned above. All 420 individual measurements involving the vision-based location of targets and the measurement of co-ordinates succeeded and the pointing precision was 0.019 mRad (std. deviation). Pointing accuracy was better than 0.04 mRad, and the accuracy of the averaged x, y and z co-ordinates deviated less than 1 mm from the reference values in 81% of the cases in which the measurement distances ranged from 4.5 to 16 m. The execution speed was 20 s per target. The performance achieved met the goals, except for the speed, which needed to be improved.

[2] A target refers here to a special mark, such as a retro-reflective tape or prism, used in industrial photogrammetry, surveying and computer vision to signal points to be measured.

Paper VII describes an application of the concept to a laser profiler as used for monitoring refractory lining wear in steel mills, which is equipped with a vision system and modified control software to improve its operative and performance characteristics, especially for automatic co-ordinate set-up. The execution speed of vision-guided target location improved significantly, and a normalised correlation based method for finding natural features was implemented. Performance tests suggested that the key goals had been achieved, in that the vision-guided co-ordinate system set-up was better in terms of repeatability and speed than its manual counterpart and some stress and work safety problems may be alleviated by its automatic operation. Tentative results of tests at a steel mill suggested that the system was feasible although improved robustness was required.

2 RELATED WORK ON CAD-BASED MEASUREMENT PLANNING AND AUTOMATED OPTICAL 3D MEASUREMENT

2.1 INTRODUCTION

Control of the dimensions and shape, i.e. the geometry, of industrial objects is recognised as an important factor affecting both productivity and quality, as stated in Chapter 1.1. Since the control of geometry is not a trivial task, planning is required before the actual execution of inspection and measurement functions in order to ensure that the goals set are met in an efficient manner.

Measurement planning has been defined by many researchers, giving different perspectives on the concept. According to Feng (1994), dimensional inspection planning is an activity intended to generate specific instructions for inspecting manufactured parts based on the product design information. The goals of intelligent vision-based inspection planning, according to Yang et al. (1994), include determining which entities (edges, etc.) should be measured, what camera locations and viewing directions should be used and how the inspection can be carried out efficiently and robustly once the image data have been acquired. Measurement planning is seen in the present work as the first step in the process of geometric inspection, followed by measurement execution and analysis of the resulting data for quality control or control of work process (see Figure 1). The purpose of the planning step is to define what geometric entities should be measured and how.

Measurement planning is based on

- product data (Feng 1994),
- essential geometric entities and their allowed tolerances,
- measurement practices, and
- characteristics of the measurement methods and tools used.

The product data may be in the form of tabulated data, engineering drawings or CAD models. Examples of essential geometric entities are the width and length of a prefabricated concrete element, or the co-ordinates of a bulkhead cross-section in a ship hull subassembly. The measurement planning must recognise these essential entities and ensure that these are measured. This choice of essential entities may be based on standards, as is the case with prefabricated concrete elements (Heikkilä 1996), or it may be based on knowledge of the critical factors in manufacturing, as is the case in ship hull assembly (Storch & Gribskov 1985, Yuuzaki & Okumato 1992, Paper IV). The tolerances associated with them also may be used in measurement planning (Heikkilä 1996). Measurement practices are defined by standards, in-house quality instructions such as ISO 9001, or established informal procedures. The characteristics of measurement methods and tools used can affect such matters as the relative placement of the measurement devices and objects to be measured.

The result of measurement planning is a plan defining

- ❑ what entities (co-ordinates, dimensions, angles, etc.) are to be measured
- ❑ what functions are to be used in measurement
- ❑ in what order the measurements are to be performed
- ❑ how the measurement device and measured object are to be placed relative to each other (viewpoint planning)
- ❑ how the co-ordinate system is to be set up.

Following example drawn from shipbuilding will illustrate the significance of measurement planning. Ship hull erection can be viewed as an assembly process in which subassemblies are joined together. If two blocks to be joined do not mate properly, because their dimensions differ too much, corrective reworking is needed, causing extra costs and time delays (Sormunen 1986, Yuuzaki & Okumato 1992, Manninen & Jaatinen 1992). For this reason, the geometry of the blocks should be checked before starting the assembly work. In addition to the short-term benefits of reduced reworking and disruption, long-term benefits can be gained, such as better feedback for estimation, better design details, establishment of the shrinkage of parts during construction, improved equipment maintenance scheduling, better information for decision-making, better worker satisfaction and, most important, improved productivity (Storch & Gribskov 1985). The geometry can be checked by measuring certain vital entities, typically co-ordinates of stiff points representing the overall dimensions of the object and also the geometrical structure of the block surfaces (Storch & Gribskov 1985, Yuuzaki & Okumato 1992, Paper IV). Selection of these vital entities, extraction of their design values and tolerances from the yard’s design data base, sorting of them into a suitable order for measurement and selection of the points to be used in setting up the co-ordinate system are the most important measurement planning tasks in this case. A wire frame drawing of a midship block with the vital points to be measured is shown in Paper IV, Figure 2.

Optical 3D measurement is a way of implementing the measurements needed for geometric control. The use of automation in optical 3D measurement has certain advantages over manual systems, see Chapter 1.1.

Automation in modern production involving small batch sizes requires flexibility, and this is especially true in the production and measurement of large industrial objects such as ship blocks, prefabricated concrete elements or refractory linings. These objects are often unique, and their production and measurement conditions cannot be controlled as well as in mass production. Therefore, flexible automation is needed both in production and when performing geometric measurements.

Flexible automation requires sensory feedback from the environment and a control method that uses this information and controls the operations. The advantages gained over rigidly programmed non-sensory systems were listed in Chapter 1.1. Practical benefits observed in two industrial cases are the possibility for automatic measurement of precisely defined entities, e.g. vital points on a ship hull sub-assembly, and the possibility for measuring the same entities repeatedly at different times, e.g. the fireproof lining of vessels used in steelmaking.

2.2 CAD-BASED MEASUREMENT PLANNING SYSTEMS

The introduction of CAD/CAM (Computer Aided Manufacturing) systems and computer controlled measurement systems has led to efforts to develop means of using CAD data for dimensional inspection planning (e.g. ElMaraghy & Gu 1987, Park & Mitchell 1989, Yau & Menq 1990, Yang et al. 1994, Newman & Jain 1995a). The survey of automated visual inspection by Newman and Jain (1995b) also emphasises the role of CAD-based inspection systems. This is seen as a way to meet the ever more stringent speed and accuracy requirements encountered in modern production (Yau & Menq 1990), since the CAD systems usually provide fairly complete geometric information on design features and it is assumed that the inspection data can be directly generated from the mathematical representation in the CAD system (Menq et al. 1992a). An additional motive for using CAD-based measurement planning instead of teach-in programming is that it can be done concurrently with product design before the first prototype exists (Stürmer & Stegmaier 1989). Several proposals and demonstration systems for CAD-based measurement planning have been developed both for mechanical co-ordinate measuring machines (CMM) and optical measurement-based systems.

The focus in this chapter is on CAD-based measurement planning research reported in the literature. The generality of the systems with respect to measurement technology and the objects to be inspected is evaluated, together with the applications reported. Since most measurement planning systems described in the literature are intended to operate only with a certain form of inspection technology, e.g. with machine vision or CMM, this is one way of classifying the measurement planning systems. The emphasis here is on systems employing optical measurement methods, mainly machine vision, but other systems are also reviewed in Chapter 2.2.3. It should be noted that the border between CMMs and optical inspection is not clear cut, as many CMMs are equipped with optical point range sensors or in some cases video cameras, and some vision systems use CMM-like mechanics for moving the vision sensor.

Another way of classifying CAD-based measurement planning systems is the level of automation involved in the planning. The systems range from interactive tools to automatic systems operating with no human intervention. The measurement planning systems reviewed here are also assessed in this respect.

Our perspective of the field of CAD-based vision research is that of dimensional inspection, whereas the research efforts in CAD-based object recognition and pose estimation (e.g. Bhanu & Ho 1987, Gunnarsson & Prinz 1987, Hoffman et al. 1989, Arman & Aggarwal 1993b, Yi & Chelberg 1994) are excluded. Similarly, the research done into measurement data based model generation (e.g. Fraas et al. 1991, Littleworth et al. 1992, Bradley & Vickers 1993, Boulanger 1993, Koivunen & Vezien 1996), sometimes referred as reverse engineering, is omitted.

2.2.1 Planning systems independent of measurement technology

Although most CAD-based approaches presented in the literature are tied to a particular measurement system, initiatives for planning systems that are independent of measurement technology do exist.

Dimensional Measuring Interface Specification (DMIS) was initiated in order to create a standardised basis for communication between CMMs, other measuring devices and CAD/CAM systems (Aubin 1987) and an automated measurement planning system using DMIS is reported by Merat & Radack (1992). This uses feature-based part models, each individual form feature having an associated Inspection Code Fragment (IFC) macro. When such a macro is called with the parameters of a certain feature, it is expanded to an IFC containing detailed DMIS commands for the inspection. A complete inspection plan is composed of numerous IFCs. The objects to be inspected are blocks, cylinders and their combinations. Tolerancing is also considered.

Feng (1994) proposes an activity model as an international standard for dimensional inspection planning with the goal of relating dimensional inspection to product design. This model is not restricted to CMMs but can also be applied to vision systems. The activities of inspection planning access design data from a STEP (STandard for the Exhange of Product model data) database and produce an inspection plan which can be exchanged between different inspection planning, CAD and CIM (Computer Integrated Manufacturing) systems. No mention is made of possible limitations on the types of objects to be inspected.

An inspection system using CAD data has been developed in a European co-operative project (Hirsch 1991). This contains software for planning and simulating inspection tasks performed by a vision system. The CAD data is imported in STEP file format and then converted into an internal format and tolerancing information is defined. The planning session generates an inspection program which is simulated before acceptance for execution in a FMS (Flexible

Manufacturing System) cell containing a mechanical scanner, CCD camera-based vision system and controllable illumination. Structured light and moiré techniques are also mentioned as possible measurement methods. Some tentative results regarding the inspection of sculptured surfaces are given in another paper on the same project (Graebling et al. 1992).

2.2.2 Planning systems for optical inspection

Many CAD-based measurement planning systems using optical inspection technology are tied to proposed or experimental machine vision systems. These are usually automatic and are limited to a certain class of objects. A special case of measurement planning is viewpoint planning, a problem widely studied in the computer vision community (e.g. Gremban & Ikeuchi 1993, Mason & Gruen 1994, Tarbox & Gottschlich 1995).

An automated computer vision inspection system with CAD model-based recognition and inspection planning subsystems capable of inspecting a class of small mechanical parts containing planar faces, slots and holes was developed by Park and Mitchell (1989). The CAD model is design feature-based and provides a way to incorporate tolerance information. The CAD data are converted into boundary representations and then a rule-based off-line recognition planning subsystem selects important vision features from the model and generates a list of 'characteristic views'. The rule-based inspection planning subsystem in turn provides view directions, a list of features to be measured, guidelines for vision-based measurement and image processing and range of permitted values. The inspection planning produces an inspection database and inspection command file. The actual inspection is essentially two-dimensional since it is done with a CCD camera without structural lighting.

Yang et al. (1994) present automatic methods for intelligent measurement planning with an active vision paradigm. CAD files can be translated into boundary representations that are understood by their system. A higher level representation of the object geometry containing semantic information and relations between the parts is generated, and this is used to produce inspection strategies and to determine the necessary measurable entities. Aspect graphs are then used to determine potential sensor locations, i.e. for view point planning, and finally the number of sensor positions is optimised for minimum camera settings and over the total path. The authors do not give any experimental results in their paper, but applicability to machined parts is proposed.

An experimental system for 3D CAD-based inspection using range images has been developed by Newman and Jain (1995a) which is capable of ascertaining gross defects, surface shape and the features and dimensions of objects containing planar or quadratic surfaces. The system proposed by Flynn and Jain (1991) is used to extract surface information from files generated with a commercial CAD package. The surface information, in the form of relational graphs, is generated automatically from the CAD descriptions, and thus automatic measurement planning is implied. A dense range map acquired with a triangulation scanner is used in the inspection. The authors claim that theirs is one of the first general-purpose inspection methods to have been tested on a set of real objects using real range images. The objects used were unfinished iron castings.

Tarbox and Gottsclich (1995) define the viewpoint planning problem as that of finding a sequence of sensing operations which are together capable of measuring every measurable point on the surface of the object, and develop algorithms for this purpose, which form a part of their IVIS (Integrated Volumetric Inspection System). The system comprises an off-line measurement planning part and an on-line part with data acquisition, registration, geometric comparison and analysis. The system is capable of receiving geometric models of the objects in volumetric octree form, typically generated from CAD models. The sensing plan can be generated automatically with one of three algorithms, which differ in computing time and the efficiency of the plan. A hypothesise and verify approach is used in the iterative planning. The data acquisition system is based on structured light and video camera and generates a sensed object model which is aligned with the reference model so that the deviations can be analysed. The planning algorithms have been shown to work with objects of varying complexity. The authors state that while the finding of an optimal plan is an intractable problem, they have presented algorithms for finding reasonably efficient ones.

An interactive measurement planning system for shipyard applications using laser rangefinding technology has been developed by Prometrics Ltd. (Prometrics 1993a). The vital points to be measured are extracted from CAD data and input to a measurement planning program based on spreadsheet software. The measurement planning software is capable of producing wire frame representations of 3D structures, see Figure 2 in Paper IV.

A CAD model-based shape inspection system was proposed by Moring et al. (1989) and elaborated later by Moring (1995). The inspection concept is based on the idea of taking cross-sections of the surface under inspection and comparing them with the corresponding cross-sections of the CAD model. Measurement planning is not described in detail, but it is stated that utility functions in CAD systems can be used for this purpose. The application domain of this system is the inspection of curved steel panels used in ship hulls. The measurement device is a scanning laser rangefinder.

2.2.3 Planning systems for CMMs

Co-ordinate measuring machines can be operated manually or under program control, the measurement program often being generated by a teach-in method. The problems associated with the commonly used teach-in programming of

CMMs, which can start only after the first prototype parts have been supplied, are pointed out by Stürmer and Stegmaier (1989).

ElMaraghy and Gu have developed an expert system for CMM inspection planning (1987), using a feature-based modelling system to represent the parts to be inspected and syntactic pattern recognition approach for finding the features to be inspected. A PROLOG-based expert system is used to generate inspection plans for prismatic and rotational parts and the measurement is performed by a CMM, after which the results are compared with the design data and tolerance information.

A practical system for CAD data-based interactive off-line programming of CMMs is reported by Stürmer and Stegmaier (1989). The system contains three sub-systems for measurement planning with respect to standard geometric features and sculptured surfaces and produces programs in Neutral Data File format, which is then translated for each CMM by a post-processor. The system is in use at the works of a major car manufacturer.

An automated inspection environment composed of an inspection specification module, an automatic inspection planning module, a CMM verification module, a CMM execution module and a comparative analysis module has been developed at Ohio State University (Yau and Menq 1992, Menq et al. 1992a). The core of the environment is a knowledge-based inspection planner that monitors the process and assists in decision-making. The specification module translates the functional requirements, tolerances, manufacturing parameters and CMM constraints into an inspection specification, on the basis of which the inspection planning module automatically generates an initial inspection plan containing inspection points and associated probing directions. The initial inspection plan is verified against collisions by the verification module, which simulates the inspection in the CAD system. The execution module then carries out the inspection with the CMM and the results, along with the design data, are processed by the comparative analysis module to produce an inspection report. The proposed environment has been implemented with a commercial CAD system and a CMM. Successful experimental results with a fairly complex turbo-charger housing have been reported. The intelligent inspection planning environment suggested by Yau and Menq is depicted in Figure 2.

The same authors have addressed the problems of aligning the measured data and the design surface exactly and determining the number of measurement points required for quality assurance (Menq et al. 1992b). The problem of optimal matching was formulated as a minimisation problem with respect to six co-ordinate transformation parameters and a new fast algorithm was developed for this purpose. A normalised sensitivity measure which correlates with the transformation error was calculated, but the question of finding the best set of points for co-ordinate system alignment remained open. The problem of finding the number of measurement points required on a surface profile was addressed by developing a statistical model which is dependent on both tolerances and manufacturing accuracy.

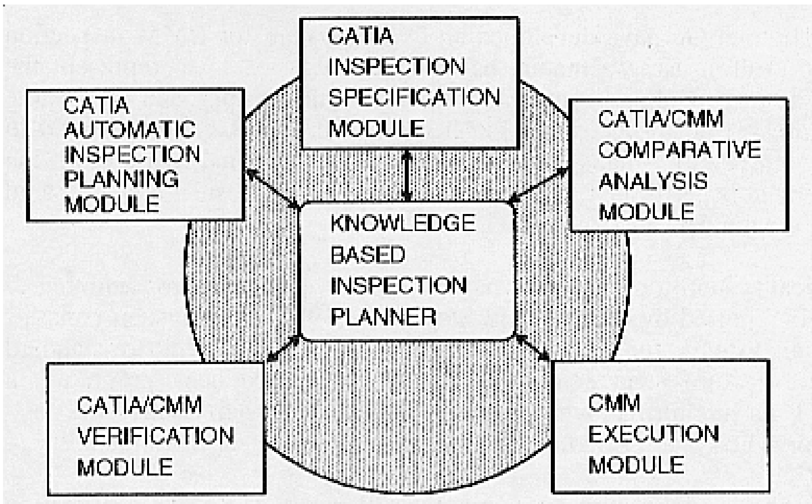

Figure 2. An intelligent inspection planning environment (from Yau and Menq 1992).

2.3 AUTOMATED OPTICAL 3D MEASUREMENT SYSTEMS

We shall now consider automatic optical 3D measurement systems for industrial applications paying special attention to the use of sensory feedback to guide the measurements. Such systems can be characterised according to the level of automation vs. human intervention involved, the type of sensor used, the repeatability, accuracy, speed and reliability of the pointing system and the requirements set for the object to be measured, e.g. whether special target marking is required. A good survey of automated visual inspection can be found in Newman & Jain (1995b).

Theodolite-based systems are reviewed in Chapter 2.3.1 and machine vision-based systems in Chapter 2.3.2, and the results of the review are discussed in Chapter 2.4. Devices with a short measurement range (see for example Ley & Becker 1992), are excluded from the discussion, since they lie outside of the scope of this thesis, nor are optical 3D measurement techniques *per se* discussed here. Surveys of range sensing (Jarvis 1993), active optical range imaging sensors (Besl 1988), stereo vision systems (Dhond & Aggarwal 1989) and the acquisition of geometric information (Moring 1995) can be found in the literature.

2.3.1 Theodolite-based systems

Theodolite measurement employs the spatial intersection method, in which at least two theodolite telescopes are pointed at the object and the corresponding vertical and horizontal angles are measured. In modern theodolites the angle readings are fed to a computer, which then determines the 3D co-ordinates of the point in question from pre-calculated orientation data. Theodolites have been equipped with laser rangefinders, and systems of this kind able to measure the 3D co-ordinates of a point with one station are often referred to as tachymeters or total stations. Theodolites and other optical co-ordinate measurement systems have also been equipped with servo motors and automatic pointing and tracking systems in order to save time or work and improve the repeatability of the measurements.

Automatic pointing to targets has been implemented using the strength of returned distance measurement signals and auxiliary sensors such as CCD cameras (Leinonen 1988, Kahmen 1992). These systems are used together with retro-reflecting targets, usually prisms for the purpose of guiding the theodolite to point at or track the target. Where a distance measurement signal is used, the theodolites have a control logic for servoing the horizontal and vertical rotation motors to point in the direction of the strongest returned signal, which is assumed to come from the centre of the target prism. A sighting precision of 10 arc seconds (0.048 mRad) in a static situation has been reported for a commercial theodolite (Topcon 1992).

A CCD camera-based vision system for aiming the theodolites at the point to be measured has been developed by Kern (Gottwald & Berner 1987, Gottwald 1988), see Figure 3. This system, called Kern SPACE, is based on electronic servo-theodolites equipped with a small video camera, an image processor and image analysis software for detecting marked points (Zhou 1986). The points may be marked with retro-reflective targets or with a projected laser spot. The accuracy of finding the target centre is reported to be 1/10 pixel. The SPACE system has control software for aiming the theodolites at the target, calculating its 3D position in object co-ordinate system, comparing this with nominal values and storing the data. An accuracy of 0.05 mm within a 3 m cube under good conditions with a measurement speed of 5 - 7 seconds per point has been reported (Gottwald & Berner 1987, Gottwald 1988). The applications suggested include automated calibration of robots, checking of the accuracy of satellite antennae and inspection of fixtures used in the automobile and aerospace industries. A similar system with a motorised theodolite equipped with a CCD camera and vision software is reported by Katowski (1992). Video theodolites can also be equipped with laser rangefinders (Leinonen 1988) so that they can operate alone without a second theodolite.

Weiqian et al. (1990) report a system with a manual theodolite equipped with a video camera and vision system for bridge model deformation measurements. The possibility of using a multi-station net is mentioned but the experiment reported was done with a one-theodolite system. The light emitting diodes used as targets were found with an accuracy of 1/10 pixels.

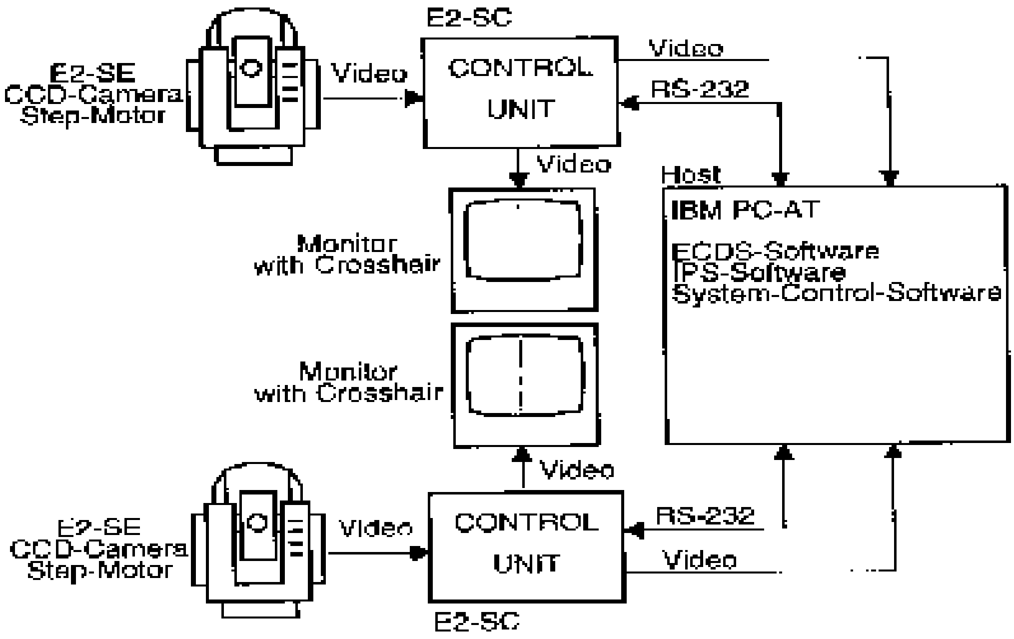

Figure 3. Kern SPACE system (adapted from Gottwald 1988).

Vision is used to enhance the angular resolution of a system developed for robot calibration (Driels & Pathre 1991). The vision-based automatic theodolite system (VBAT) has servo motor driven horizontal and vertical rotation stages with an angular resolution of 0.01 degrees (0.17 mRad). The angular resolution achieved with the vision system is reported to be 0.0005 degrees (0.0087 mRad). An elaborate calibration method has been developed for the VBAT system and after calibration the system is capable of determining the position of an illuminated sphere to an accuracy of 0.2 mm at a distance of 4 m (0.05 mRad). The VBAT can track the illuminated target automatically and at the same time adjust the focusing distance of its zoom lens. Due to its intended application, the system is of a rather bulky construction and not very portable.

A laser radar for industrial shape measurements with tracking capability is described by Mäkynen et al. (1994). The pointing solution is based on illuminating a retro-reflective target point and focusing the reflected light on a PSD, which provides the electrical signals controlling the measurement head. A resolution of 0.003 mm (σ value), bias of +- 0.1 mm and pointing accuracy of 0.3 mm in a measurement range of 2 to 5 m (0.06 mRad) are reported under controlled laboratory conditions using a 10 mm diameter reflector. Tentative results indicate a pointing accuracy of 1 mm under industrial conditions and working distances of up to 12 m (0.083 mRad). The speed of the pointing is limited by the measuring head motors and not by the tracking and pointing detector. Applications for the measurement system are expected to be found in shipyards and construction projects, etc.

2.3.2 Machine vision based systems

Several automatic 3D inspection systems based on computer vision and photogrammetry have been proposed and implemented.

El-Hakim et al. (1992) developed a Vision-based Co-ordinate Measuring system (VCM) for co-ordinate and dimensional measurements of parts typically used in the aerospace and automobile industries. This is a multi-camera passive system combining stereo vision and photogrammetric techniques with CAD-based feature extraction. Object models consisting of labelled edge points can be generated from CAD data and drawings or by training. The inspection procedure is divided into a data acquisition step and an inspection step, which operates with labelled points and is thus independent of the measurement technology used. The data acquisition step comprises two tasks. First, the part is located using prominent features such as holes, after which a 3D wire frame model of the object is projected in the images and used to help in locating interesting features such as edges. In this sense, guidance is used to focus the search for features to be measured. A repeatability of 0.008 mm (std. deviation) with objects of diameter of 25 cm (1 : 31000 relative precision) is reported under controlled conditions together with a bias of 0.013 mm (RMS) (1 : 19000). This system developed by the National Research Council of Canada is used in industrial and medical applications.

An experimental Vision Measurement System (VMS) for automatic non-contact geometric measurements on industrial objects of various sizes was developed at General Dynamics (Schwartz 1989). The system is composed of Vision Metrology Units each containing a two-axis vision head with a video camera, special zoom optics and a laser for projecting active targets. The system can operate in theodolite mode to measure the co-ordinates of separate points, in photogrammetry mode to utilise the full field of the CCD camera or in machine vision mode for 2D inspection. The volumetric accuracy of the system was evaluated using a Volumetric Accuracy Test developed for the evaluation of CMMs. An accuracy of 0.07 mm (std. deviation) inside a volume of 1.67 x 1.22 x 1.54 m (relative accuracy 1 : 24000) is reported. Proposed applications include inspection of the dimensions and shapes of tanks, aircraft and submarines and also teleoperation.

Automatic and semi-automatic photogrammetric systems for industrial inspection and measurement have been implemented. Maas and Kersten (1994) report an experiment with the use of a semi-automatic photogrammetric system for geometric control at a shipyard. Here a digital still video camera was used to acquire images of the hull section for a ship with vital points indicated by means of retro-reflective targets. The images are analysed semi-automatically, in that the user identifies 4 - 6 points on each image manually in order to perform an approximate orientation and then identifies all the points to be measured at least on one image, while the rest of the processing is done automatically by means of a software package. Full automation is not deemed possible in this task due to the high robustness and flexibility demands. A relative accuracy of 1 : 40000 is claimed in the shipyard case.

A photogrammetric system for the automatic measurement of car body orientation has been developed for a robotic seam sealing application (Haggrén 1993). A set of permanently positioned video cameras is used to acquire images of the car body, and a vision processor with a special software package analyses these images and determines the orientation of the car body by finding known holes on its underside. A practical measuring accuracy of 0.2 mm (mean standard error), or a relative accuracy of 1 : 10000, is reported. The system has been in production use for many years. Photogrammetric inspection systems for industrial inspection have also been reported by Luhmann (1990) and Pettersen (1992).

2.4 DISCUSSION

The objective of measurement planning can be stated as being that of defining the measurement set-up, choosing the relevant geometrical features to be measured and arranging the order of the steps. Furthermore, the resulting measurement plan must be in a form in which it can be understood by the agent performing the task, whether a human operator or an automatic machine.

The traditional form of geometric control is based on design drawings and manual measurement methods, without any use of computers in measurement planning. Since CAD/CAM systems have become widely used, the idea of using design data in CAD format as a basis for measurement planning has been put forward. This is motivated by following arguments: design data for the objects to be inspected readily exist in the form of CAD files, CAD data contains sufficient geometric and tolerancing information for the product to be measured, and this information is in an electronic format that makes it transferable to other computer systems thus facilitating automatic measurement planning and execution. Also, the use of CAD data is assumed to speed up the measurement planning, since such data are available even before the first prototype exists. An additional advantage is that the direct utilisation of geometrical information available in modern CAD databases eliminates many unnecessary and potentially error-prone steps of working with paper print-outs or intermediate file types. Furthermore, when using CAD files it is natural to build graphical, easy-to-use computer-based tools for measurement planning, which in turn makes the measurement planning more efficient.

Most CAD-based measurement planning systems reviewed are tied to a specific measurement system and its devices. In particular, vision and CMM based systems are proposed. Some device independent systems are also presented, however, in the context of Dimensional Measuring Interface Specification. Standardisation would be desirable in the sense that the measurement planning systems developed could benefit users independently of the measurement device and its application.

The systems reviewed use various CAD formats, including vendor specific commercial and experimental file formats and formats conforming to the IGES standard. Compatibility with a wide range of CAD systems was not emphasised in the papers concerned, probably because of the experimental nature of the systems.

Automation was the goal of the majority of the CAD-based measurement planning systems reviewed in Chapter 2.2, and measurement planning is seen as an integral part of automatic inspection systems employing vision or CMM measuring devices. As no human intervention is assumed in these systems, they rely heavily on *apriori* information, e.g. in the form of conventional programs or rule-based systems. This approach limits the flexibility of the system, since all possible situations should be anticipated when programming or teaching the system and it is for this reason that the systems reviewed are limited to operating with a certain class of objects, e.g. small machined parts containing planar and circular surfaces. Newman and Jain (1995b) make a similar remark on automated inspection systems in general, that they tend to be specialised for the inspection of a single part or object class.

Another drawback of fully automated measurement planning systems is the lack of semantic information in conventional CAD representations (Kaarela 1996), which places heavy requirements on the systems, which should be capable of finding the vital entities to be measured in an efficient manner.

An intermediate approach between traditional measurement planning and the fully automated approach would be interactive computer aided measurement planning. The following arguments may be presented in favour of this approach:

- ❑ Information contained in CAD models can be fully utilised in measurement planning.
- ❑ The familiar methods and tools available in CAD environments can be used in measurement planning.
- ❑ The resulting measurement plan can be generated directly in computer and human readable formats.
- ❑ Use is made of human knowledge and judgement.
- ❑ Human flexibility and intelligence is combined with the speed and accuracy of a computer.
- ❑ In some cases measurement planning can be carried out concurrently with product design.

The idea of using a computer as an advanced planning aid is similar to that in computer aided design and the off-line programming of robots. The arguments given above lead us to believe that the computer aided measurement planning approach is feasible and advantageous.

An interactive system for measurement planning is proposed in Paper I, and its implementation producing a measurement plan executed by a robot, is described in Paper II. An example of measurement planning in a shipyard application can be found in Paper IV. Measurement planning as a part of the concept of CAD model-based automated 3D measurement and the implementation of a CAD-based planning tool is described in Papers V and VI, together with feasibility experiments.

The automation of optical 3D inspection is being pursued for its economic benefit, work safety considerations and improved repeatability, reliability and speed. Flexible automation is required especially in the manufacturing of large industrial structures and in modern production with small batch sizes. One way of introducing flexibility is to use sensory feedback to guide the measurements to the features of interest.

Automatic optical 3D measurement systems based on theodolites and tachymeters were described in Chapter 2.3.1, and systems based on machine vision or photogrammetry in Chapter 2.3.2. Particular emphasis was placed on the use of sensory feedback to guide 3D measurement. In the case of automatic theodolites, the vision system is used to replace the human operator at the aiming stage. The motivation for doing this is reduced man power costs, improved repeatability and speed and elimination of human errors, especially in tedious and repetitive tasks. Applications of video theodolites include checking of dimensions of large structures, robot calibration, measurement at construction sites and geometric control in the aerospace, automobile and shipbuilding industries (Gottwald 1988, Weiqian et al. 1990, Katowski 1992).

The automatic aiming of theodolites is typically based either on reflected signal strength or location of a target with an auxiliary sensor, e.g. a CCD camera. Both operating principles require the use of special targets. Pointing accuracies between 0.02 mRad and 0.1 mRad are reported, and the time taken is typically a few seconds. The cases reviewed pay little attention to planning of the measurements, and no systems explicitly including CAD-based measurement planning in connection with sensor-guided co-ordinate measurement have been reported. The automatic pointing systems presented usually depend on special targets, e.g. prisms, which have to be positioned manually, thus undermining the advantages of automation.

The systems using machine vision and photogrammetric techniques for automatic geometric inspection that were reviewed have an intrinsic capability for using vision to locate the objects to be measured and for pointing the certain features, such as holes, corners and edges. Applications include the inspection of machined parts (El-Hakim et al. 1992) and the measurement of large industrial objects (Schwartz 1989). The repeatability of video camera-based stereo or photo grammetric systems varies according to measurement conditions, camera positioning and camera resolution. Relative precision ranging from 1:10000 to 1:40000 of the measurement area are reported. The use of CAD models as reference data is seen to be desirable by many researchers and some of the systems reviewed have a provision for using these as a source of information. The systems reviewed can be used to inspect visible features such as edges and holes without special targets, but the measurement of featureless surfaces or operation under difficult conditions may require targeting (El-Hakim et al. 1989, 1992, Maas & Kersten 1994).

The characteristics of four of the systems reviewed are summarised in Table 1. No direct comparison based on the figures in the table can be made, since the performance of the systems has been measured under widely differing conditions and the applications for which they are intended vary greatly.

Table 1. Characteristics of automated optical 3D measurement systems.

	Kern SPACE	Acman 200	VCM	Mapvision
Measurement method	theodolite	AAR	photogrammetry, stereo	photogrammetry
Feed-back	CCD camera, image analysis	PSD	photogrammetry, stereo	photogrammetry
Level of automation	semi-automatic or automatic	semi-automatic or automatic	automatic	semi-automatic or automatic
Typical use	large industrial objects	shipyard: plates, structures	automotive & aerospace parts	car body
Accuracy /object size or distance	0.05 mm in 3 m cube (1:60000)	1 mm /12 m, distance (1:12000)	0.013 mm / 25 cm, size (1:19000)	0.2 mm / 2 m (1:10000) car body case
Speed	5 - 7 s / point	1 - 5 s / point	-	< 1 s / point

The use of sensory feedback to facilitate automatic geometric measurement has been proposed and this has been implemented in experimental and practical systems. The results reported in the literature show the feasibility and advantages of this approach. When combined with the use of existing CAD models as sources of reference data, this approach is well suited to modern production requiring cost-effective manufacturing and generating products that meet tight geometric quality norms.

Our approach here was to combine interactive CAD model-based computer aided measurement planning with automatic vision-guided laser rangefinder-based 3D measurement. This vision-based approach facilitates the use of both special targets and natural features. A laser rangefinder-based system for automatic 3D measurement is described in Paper III, while Papers V, VI and VII contain justifications of the use of vision as a sensory feedback with automatic 3D measurement. Also, two implementations are described and their performance evaluated.

3 THE CONCEPT OF CAD MODEL-BASED AUTOMATED 3D MEASUREMENT

This chapter elaborates on the concept of CAD model-based automated 3D measurement as presented in Chapter 1. The overall concept, shown in Figure 4, divides the geometric measurement into two actual steps and the subsequent analysis and use of the results:

❑ Measurement planning (interactive)

❑ Measurement execution (automated)

❑ Analysis and use of the results

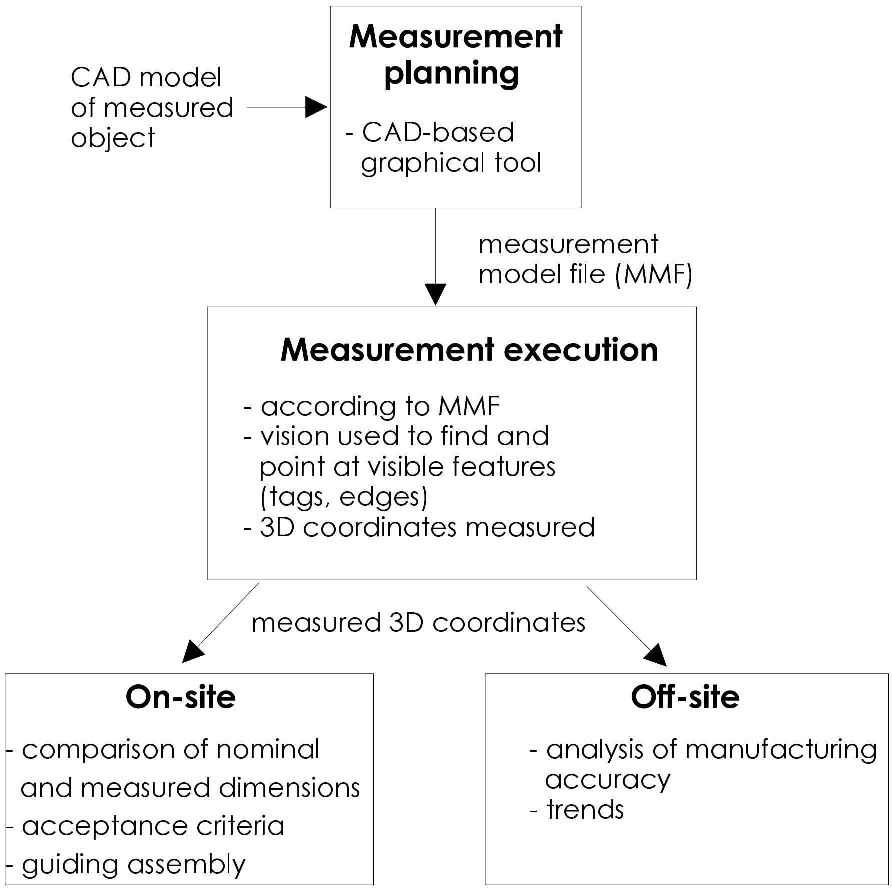

Figure 4. The concept of CAD model-based automated 3D measurement (from Paper VI).

The measurement planning step uses existing CAD models of the object to be measured as a starting point, the designer making use of CAD-like tools for planning the entities to be measured, measuring methods and measurement device position. The entities to be measured can be points, distances between two points, profiles or areas, for example and the methods can be measurement of targeted points with sensory feedback or measurement of non-targeted points using given co-ordinate or angle values to control the measurement device. Additional functions for verifying of the feasibility of the measurement, e.g. visibility checking, may be provided in the planning system. The results of the planning are saved in a computer-readable format.

The measurement plan is read by the control computer of the measurement system, which performs the measurement sequence accordingly. Sensory feedback can be used to guide the measurement to the desired points, and in principle to detect outliers in advance.

The measured and design geometry can be compared immediately after the measurement, so that the results can be used at once to guide assembly, for example, or later to assist the statistical analysis of manufacturing accuracy. This step lies outside the topic of this work, however and is only touched on here briefly.

An example of measurement planning and execution at the general level is the following:

1. The measurement sequence is planned using the measurement planning tool and a CAD model of the object. This produces the measurement model file (MMF).
2. The object to be measured is brought into the measurement position.
3. The user chooses the corresponding MMF and starts operation.
4. The measurement system operates according to the MMF, and the user sees the messages and intermediate results as the operation advances. A typical operation sequence would be as follows.

4.1 Align with the world co-ordinate system represented by fixed targets with vision guidance (this could be used as a self check).

4.2 Set up the object co-ordinate system by measuring three or more set-up points with vision guidance.

4.3 Measure the targeted points with vision guidance.

4.4 Measure the non-targeted points with two given co-ordinates (blind measurement).

4.5 Measure points on an edge by following the edge with vision guidance.

4.6 Save nominal and measured co-ordinate values and their differences in a data file.

5. After MMF execution, control is returned to the user.

3.1 CAD MODEL-BASED MEASUREMENT PLANNING

Measurement planning is seen as a necessary step for the efficient control of product geometry (Feng 1994). Arguments for using CAD data in measurement planning were reviewed in Chapter 2, where the adoption of CAD-based interactive measurement planning was justified. This intermediate approach combines the advantages of automatic and manual measurement planning.

The following requirements were set for measurement planning:

- ❑ compatibility with existing CAD design formats,
- ❑ a graphical user interface, and
- ❑ a measurement plan produced in a form readable by automatic measurement systems and humans.

Compatibility with existing CAD design formats is necessary in order to utilise the information on object geometries contained in existing CAD models. The versatility of system-specific CAD design formats presents a problem here, however, since this has led to difficulties in exchanging data between systems (Kaarela 1996). Attempts have been made to solve this problem by developing translators betveen various systems and by standardising data formats. The drawback of translators is that a separate one is needed for each pair of systems, leading to very large number of translators. Initial Graphics Exhange Specification (IGES) defines a neutral file format for geometric information (IGES 1988), but the problem is that it is not widely supported by commercial CAD systems (Teeuw et al. 1995). In this situation, data formats supported by leading CAD suppliers, like DXF in AutoCAD[3], have become de facto standards (Teeuw et al. 1995). Since no universal CAD design format exists, the CAD design format used in the measurement planning system should be chosen so as to ensure that the widest possible compatibility is achieved and no foreseeable applications are excluded.

Graphical representation of design and visually oriented tools is a crucial factor for creating an efficient computer aided design environment. Similarly, a graphical user interface enhances the work of measurement planning, making it easier for the operator to visualise the measurement situation and helping man-machine communication. An additional benefit is achieved if the measurement planning user interface offers tools and functions that are familiar to the operator. This can be achieved, for example, if they are similar to those used in CAD systems.

A capability for checking the visibility of features to be measured would be of great value to the user and this could be developed further into a function verifying the measurement plan against given preconditions, e.g. measuring distance, the type of target or surface material and the angle between the surface and the direction of measurement. This function could also be enlarged to give error estimates for the planned measurements.

The measurement plan should contain the necessary information for controlling the automatic sequence executed by the measurement system by means of vision guidance. A typical measurement sequence would contain a world co-ordinate system set-up function, which can also be used for diagnostic and calibration purposes, an object co-ordinate system set-up function and a varying number of

---

[3] AutoCAD is the registered trademark of the Autodesk Company.

measurements. An advantage will be gained if the measurement plan is in a form understandable by a human operator, so that he/she can check the plan before execution, for example, or solve any problem situations that may arise. In addition to the actual measurement control information, the model could contain identification data for operators and computers and textual data for operators.

The structure, key words and parameters used in the measurement model file (MMF), the structure of which is presented in Figure 5, must be defined. An example of a Measurement Data Block in a MMF is contained in Figure 6, where two parts of the block defining the information for the co-ordinate system set-up (left column) and for a retro-reflective target (right column) are shown. The left column defines the number of points to be measured and the co-ordinates of the three points used in co-ordinate system set-up (WCS stands for World Co-ordinate System). The right column defines the point identification (RETROPOINT1) and the target type (R20), and gives its location in the user co-ordinate system (UCS) in mm, the normal vector of the target (NORMAL), the nominal distance from the measuring device (DISTANCE) and the apparent narrowing and shortening of the target due to the viewing angle (NARROW and SHORTEN) in degrees.

START BLOCK
HEADER BLOCK - identification information
MEASUREMENT DATA BLOCK - world coordinate system setup data - user coordinate system setup data - measurement device position - nominal data for measurement, e.g. feature type, position, normal direction
APPLICATION-SPECIFIC BLOCK - user defined data
END BLOCK

Figure 5. Structure of the MMF (adapted from Paper V).

NUMBER OF ALL POINTS:	*RETROPOINT1*
17	*R20*
WORLD COORDINATE SYSTEM	*26185.7*
SETUP:	*1.08952*
3	*-1956.79*
WCS_POINT1	*NORMAL*
0.0	*1.0*
0.0	*0.0*
0.0	*0.0*
WCS_POINT2	*DEVICE1:*
13210.0	*DISTANCE*
0.0	*18424.8*
0.0	*NARROW*
WCS_POINT3	*24.9921*
0.003	*SHORTEN*
0.0	*7.2258*
2197.0	

Figure 6. Part of a measurement model file (adapted from Paper V).

3.2 AUTOMATIC MEASUREMENT EXECUTION

3D measurement with optical rangefinder-based co-ordinate meters can be made more automatic and versatile if the system can automatically find the desired measurement points and point at them (see Chapter 2.3). This ability makes the measurement system adaptable to changes in the relative positions of the object and measuring device and in the actual shape of the object. Additional benefit could be gained if intelligent sensors could monitor the co-ordinate measurement and detect outliers prior to measurement. Furthermore, the sensors could provide information in a form readily understood by human operators in teleoperation applications.

The measurement system must be able to transfer the measurement plan into specific actions producing the desired results. If the measurement plan takes the form of a special file consisting of key words and parameters, it can be interpreted by a parser activating functions related to the key words found. The parameters convey information such as the type of feature measured and nominal co-ordinates. If the measurement plan is in the form of a data structure with each element having pre-defined position and meaning, more rigid software can be used to control the execution stage. The first alternative gives substantial freedom in the planning step and makes the whole measurement process more flexible, while the latter is more suitable for application-specific measurements, where many things can be fixed beforehand and less flexibility is required.

Flexibility may be attained by the use of sensory feedback. In the concept presented here, this is specifically guided by the measurement plan. For example, if an entity to be measured is first to be located using vision, this should be coded into the measurement plan along with the information needed by the vision system. An example of how sensory feedback, in this case vision, may be used to guide the measurement is given in the pseudocode of Figure 7. The measurement head is pointed towards the nominal position of the point to be measured based on data read from the measurement model file, and then the vision system is used to guide the measurement head until it points towards the desired point.

```
read the nominal co-ordinates of a point from the MMF
transform the co-ordinates into the sensor co-ordinate system using transformation
matrices generated in the co-ordinate system set-up phase
point the measurement head towards the nominal position of the point
transfer control to the vision system
generate/fetch a model of the target based on distance, attitude and type or a model
known from the MMF
    WHILE rangefinder pointing not within tolerance
            acquire an image
            search for the point
            IF point found
                    transform the camera co-ordinates into horizontal and
                    vertical difference angles
                    drive the measurement head
            END IF
    END WHILE
```

Figure 7. Algorithm for vision guidance.

3.3 DISCUSSION

A concept for CAD model-based automated 3D measurement is presented here, which divides geometric control into two steps: CAD model-based interactive measurement planning and automatic measurement execution using sensory feedback followed by the use of measured data, typically for comparison of as-designed and as-measured values.

CAD model-based measurement planning has several advantages over more traditional paper document-based or ad hoc methods in modern industry (see Chapter 2). These include at least

- ❏ possibility to use the fairly complete geometric representations contained in the CAD models (Menq et al. 1992a),
- ❏ possibility to start measurement planning concurrently with product design (Stürmer & Stegmaier 1989),
- ❏ possibility to use directly existing CAD models of the objects, e.g. without intermediate paper print-outs,
- ❏ possibility to utilise the CAD package to implement tools for computer aided measurement planning,

- ❑ possibility for view point planning and verifying the measurement plan against preconditions, e.g. measurement range,
- ❑ possibility to produce control files for measurement devices or measurement robots automatically.

As stated in Chapter 2.2, several proposals and systems for CAD-based measurement planning have been put forward. Typically, the goal has been an automatic measurement planning system capable of producing measurement plans or programs from the CAD models without human intervention. This approach has limited the flexibility of these systems, and they are in most cases restricted to a certain class of objects and some specific CMM or optical measurement device. In any case, the automatic planning operation rules out the possibility of using human knowledge at the measurement planning stage.

Sensory feedback is an important element for flexible automation. Sensors are employed with industrial robots, for example, when flexibility is required (Critchlow 1985, Klafter et al. 1989, p. 315). This has already been shown to be feasible for guiding optical 3D measurement (Gottwald & Berner 1987, Gottwald 1988, Katowski 1992, El-Hakim et al. 1992, Kilpi et al. 1992).

In the concept presented here, CAD model-based measurement planning is combined with sensor-guided 3D measurement. The application domain, i.e. the class of objects whose geometry is to be controlled, the measurement techniques used in 3D sensing and the guidance provided for the measurement are not limited by the concept.

The evolution of the concept is described in Papers I, II and V - VII. The idea of inspection planning for automatic 3D inspection as presented in Paper I divides the inspection phase into an off-line planning phase performed concurrently with product design and an on-line inspection phase. A set of device-independent inspection functions is proposed in order to avoid unnecessary detail in the planning phase. The implementation of these functions in the inspection phase is device-dependent. The use of feedback from previous measurements is proposed for point-measuring 3D sensors.

The ideas presented in Paper I are developed further in Paper II. The inspection task is seen as a three-step process adding analysis of the inspection results to the two steps mentioned in Paper I. A graphical interactive measurement planning tool, an interpreter to transfer measurement plans into actions, the measurement system and software to analyse the measurement results are named as the basic elements for a computer aided measurement planning system for 3D inspection. The use of CAD models in measurement planning is emphasised, and it is suggested that the measurement planning tool might be built on a CAD package.

The concept of CAD model-based automated 3D measurement is elaborated in Papers V and VI. The idea of using sensory feedback to make the automatic measurement more flexible is emphasised and the use of auxiliary sensors for this purpose is suggested. The measurement planning tool was built on an existing CAD package, as suggested in Paper II.

The concept is extended to a monitoring application in Paper VII. The role of sensory feedback in improving the repeatability of the measurements, avoiding human errors and saving time is stressed. The use of an auxiliary sensor for providing information for use in the measurement planning phase is suggested.

The feasibility of the concept is tested by implementing experimental systems and demonstrating their operation in experimental cases drawn from industrial applications. These topics are covered in Chapter 4. The results are discussed and analysed in Chapter 5.

4 EXPERIMENTATION

The feasibility of the concept of CAD model-based automated 3D measurement was tested by experimentation. A research prototype measurement planning tool and two experimental vision-guided laser rangefinder-based co-ordinate measuring systems were designed and implemented and their performance and feasibility tested in laboratory experiments and with demonstration cases drawn from the shipbuilding and steel industries. Although the difference between the feasibility of the concept and the properties of the current implementation must be kept in mind, it is our belief that this experimentation gives a good indication of the feasibility of the concept.

The requirements, implementation and tests for the experimental systems are described in this chapter. The measurement planning tool is discussed in Chapter 4.1, the vision-guided co-ordinate meter systems in Chapter 4.2 and the demonstration cases in Chapter 4.3. The implementation and feasibility of the experimental systems is also discussed in Papers V - VII.

4.1 MEASUREMENT PLANNING TOOL

The computer aided measurement planning tool is a graphically oriented interactive environment for producing measurement plans in the form of a measurement model file (MMF) which is understandable to the control computer of the measurement system. The following requirements were set for measurement planning in Chapter 3.1: compatibility with existing CAD design formats, a graphical user interface for measurement planning, and a measurement plan produced in a form readable by automatic measurement systems and by humans. In addition, practical considerations led to certain further requirements: a PC host computer was preferred for cost and availability reasons, the tool should be based on a well known development environment for credibility reasons, and ease of programming favoured a system with ready-made functions yet having an open development system.

The format and semantics for the measurement plan file were also defined (see Chapter 3.1) and the measurement planning tool was required to be able to produce such a file without extra work on the part of the user.

The implementation described here was preceded by a simple measurement planning tool based on a graphical software package (see Paper II) which was used for planning measurement sequences performed with a scara robot equipped with an optical point ranging sensor. The ideas and experience gained in this early work were used when specifying and designing the current implementation.

4.1.1 Implementation of the measurement planning tool

Several alternatives exist for implementing the computer aided measurement planning tool, including

- ❑ coding with languages such as VisualBasic, which provide graphical support,
- ❑ using packages offered for implementing custom-made CAD systems (Disc Software 1994),
- ❑ graphics software packages and
- ❑ development environments provided by various CAD vendors.

The last alternative was chosen, because it provides reliable, tested CAD file compatibility, highly developed user interfacing capabilities and a programming environment with a large number of ready-made functions for manipulating geometric models. Among the various commercial products, AutoCAD was chosen primarily because it is probably the most common PC CAD system and an industrial standard in a sense (Teeuw et al. 1995). It should be kept in mind, however, that the environment in which the computer aided measurement planning tool is implemented is not critical, since the same functions could be implemented with the other alternatives mentioned. The implementation presented here should be regarded only as one possibility, chosen according to the state of our knowledge at the time.

The tool is implemented using the development environment provided by the AutoCAD version 12. package with the Advanced Modelling Extension (AME). Most of the programming was done in AutoLISP, relying on the functions provided in the development environment.[4] The user interface was implemented using Dialog Control Language (DCL) and Direct Interpretively Evaluated String Expression Language (DIESEL). For a detailed description of the first implementation, see Kallio-Kokko (1994).

The structure of the measurement planning tool software corresponds to the menu structure visible to the user, as shown in Figure 8. On the first level, the user can choose between file, edit, plan and lay-out functions. The file functions are intended for importing CAD files (DXF format), opening existing measurement models in CAD format (MMD-files) and creating and saving measurement models as text files readable by the measurement systems. The edit functions comprise a set of tools for manipulating the objects on the screen, while the plan and lay-out functions constitute the core of the tool. The lay-out functions are used to position the rangefinder in the model of the measurement site and the co-ordinate system set-up functions are used to set up the world co-ordinate system (WCS) and the user or object co-ordinate system (UCS). In addition, several functions are provided for positioning the cameras in a real-time photogrammetric system and

[4] An alternative means of implementation would have been to use C-language for coding. AutoLISP was chosen because easier and less laborious development was given priority over the faster execution achievable with C-language.

adjusting them, but this part of the measurement planning tool lies outside of the scope of the present thesis (see Oksanen 1996). The plan functions are used for planning the actual measurement. Four types of measurement can be chosen: 3D point, edge, curve and surface. 3D point measurement includes planning of both the measurement of targeted points with vision guidance and the measurement of plain points according to two predetermined co-ordinates (Moring 1995). Edge measurement is used to plan measurements based on vision-guided edge following, the curve function is for planning the measurement of cross-section pointed by the user, and the surface function is similarly for planning raster-like measurement operations where the intention is to measure points in a rectangular area with a given density.

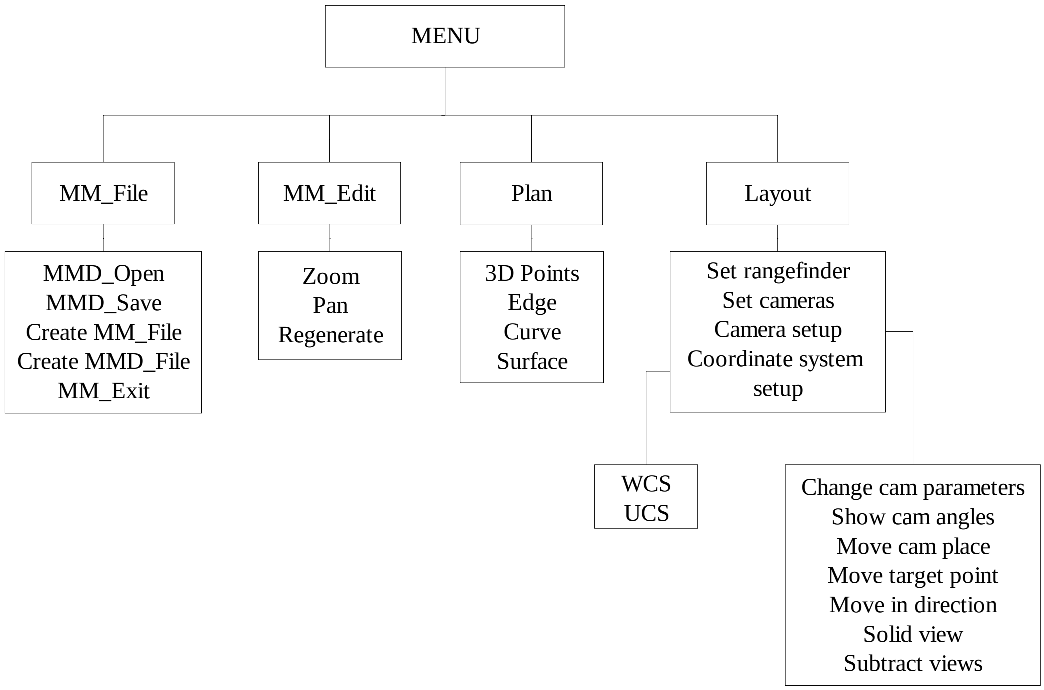

Figure 8. Structure of the measurement planning tool menu.

Although the measurement planning tool was designed primarily for AAR devices, its use for planning of photogrammetric measurement set-ups was not overlooked. Functions for camera placement and viewpoint planning were implemented. The tool was developed further by integrating it with measurement uncertainty estimation software (Oksanen 1996).

Based on the viewpoint planning functions implemented for photogrammetry systems, a special function for a converter measurement application was implemented. In this application the measurement planning tool is used to assist the personnel in finding the optimal positions (viewpoints) for the measurement system under conditions in which the shape and size of the opening of the converter is changing due to slag formation. The goal is to be able to minimise the time and measurement positions used and yet be able to measure all the relevant areas inside the converter. In the implementation, the 3D data describing the shape of the converter opening which was captured with the vision sensor of the laser profiler (see Chapter 4.2) is read in the measurement planning tool and modelled as a polygon. The area seen by the measurement system inside the converter can be approximated and visualised for each measurement system position and converter inclination.

The commercial CAD package based implementation proved to be viable, but the programming work was more laborious than expected, for the following reasons. No ready-made functions existed for implementing many of the somewhat atypical needs we had, leading to detour-like implementations. The data structures in the CAD system are designed with a view to product design, and the data required for the measurement planning applications had to be extracted in some cases by an exhaustive search, causing extra programming work and delays in operation. Also, some difficulties were encountered with the handling of rotational objects in 3D.

4.1.2 Experiments

The feasibility of the measurement planning tool concept was evaluated with experiments using the research prototype. The general procedure of measurement planning and two examples of the use of the tool are given and the experience gained is described. The use of the tool as a part of the demonstration cases is discussed in Chapter 4.3.

The general procedure of a measurement planning session for geometric control measurements performed with an AAR device is as follows.

1. Open the CAD model of the object to be measured
   - the existing CAD model is either imported or generated with the modelling functions of the CAD system
   - alternatively, an existing measurement plan (in AutoCAD DXF compatible MMD format) can be opened and edited
   - a graphical model of the measurement space (e.g. a factory floor) may be used as a background to help the user in orienting in the virtual 3D space
2. Position the measurement device relative to the object to be measured in the model corresponding to the actual measurement space
3. Set up an object-related co-ordinate system
   - the co-ordinate system is defined by giving its origin, the direction of the x axis and a point on the x-y plane
   - transformations between the object (user) co-ordinate system and the world co-ordinate system are generated automatically with AutoCAD functions
   - targeted points and vision guidance is typically used in co-ordinate system set-up

4. Plan measurement: choose the points, edges, areas or cross-sections to be measured
   - points, edges and cross-sections which are important in the assembly should be chosen
   - the measuring of a targeted or plain point can be planned by pointing with the mouse or keying in the relevant co-ordinate values
   - vision guidance is used with targeted points and edges
   - plain points, areas and cross-sections are measured without vision guidance
   - the measurement of given edges, rectangular surface areas and cross-sections can be planned in the same fashion, the software generating automatically the corresponding individual points on the edge, in the area or on the cross-section (the spacing between the points to be measured can be adjusted)
   - planned actions will be saved temporarily in attributes and lists in AutoCAD
   - the target can be zoomed and panned on the screen if necessary
5. Verify the measurement plan
   - the visibility of the points to be measured from the measurement device is verified automatically
6. Save the measurement plan
   - the measurement plan is translated into MMF format and saved
   - the same data can also be saved in DXF compatible MMD format for later editing, see step 1

In the first example the measurement planning tool was used to plan a measurement sequence in which a set of known targeted points in a large hall were measured. A screen of the measurement planning tool with a model of the large hall at VTT Electronics which was used for the feasibility and performance testing, is shown in Figure 9. The screen is split into three windows, each showing the measurement lay-out from a different view point. The upper left window is from above, the lower left is an oblique view and the right window is from behind the measurement device. All the views can be zoomed, panned and rotated. The actual measurements were performed with an AAR device, see Chapter 4.2.

In the second example the tool was used to experiment with a converter measurement viewpoint planning task motivated by the need to choose beforehand the laser profiler locations from which the interesting parts of the lining could be measured. The task is complicated by slag (waste) forming at the opening of the converter which limits the free view. To resolve this task, a vision sensor was used to input data on slag formation into the CAD model of the converter used in view point planning. An image

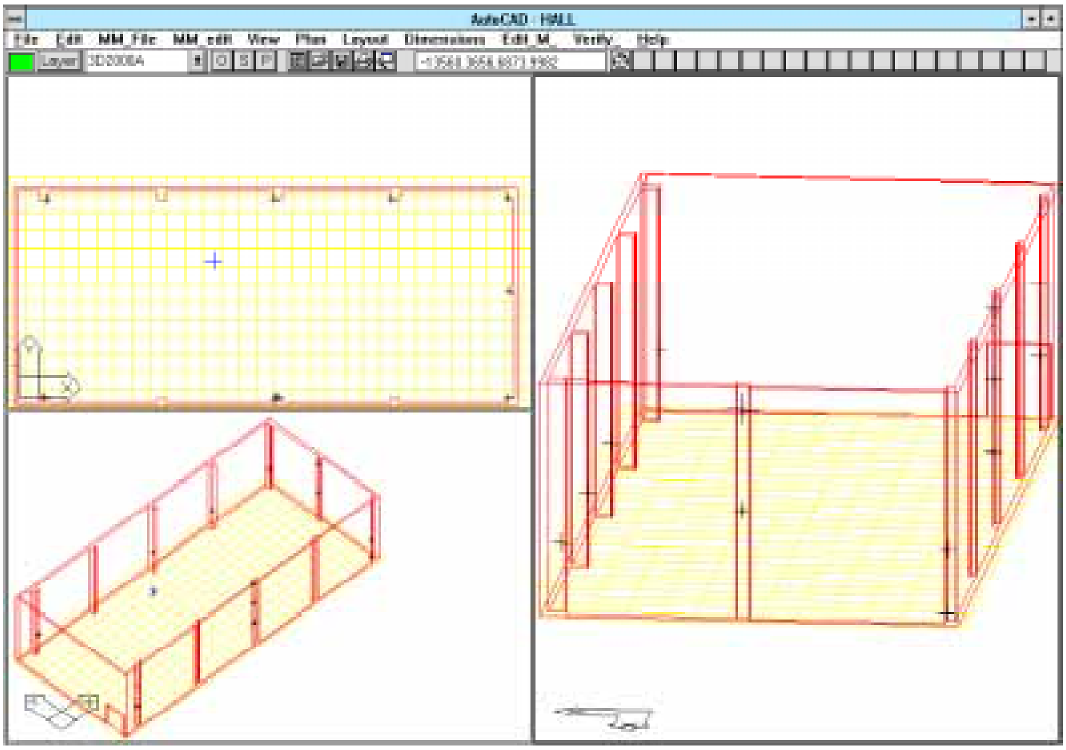

Figure 9. A screen of the measurement planning tool (adapted from Paper V).

analysis method for finding the dark circumference (slag) around a bright area (converter opening) was implemented. The circumference is described by a polygon in the camera co-ordinate system where upon the co-ordinates of the vertices of the polygon can be transformed into a 3D measurement instrument co-ordinate system and then to the converter co-ordinate system. The 3D co-ordinates of the polygon can then be imported into the CAD model of the converter. The user can not only use the nominal shape of the converter in view point planning, but can also take the effects of slag formation into consideration. The experiments showed the feasibility of the idea of visualising the measurable region in the converter in the 3D CAD model. A screen with a free view, as seen by the measurement system inside the converter high-lighted is depicted in Figure 10.

The measurement planning tool was successfully used for interactive CAD model-based graphical measurement planning in the experiments, producing measurement plans in the defined MMF format. Some drawbacks in the current implementation are evident, however. The data processing associated with the indication of points or edges, for example, is rather slow due to the AutoLISP implementation (C-implementation would have probably been faster). The general level of user friendliness in the user interface is naturally still at a research prototype level, so that the 3D line drawings were difficult to interpret correctly in some cases.

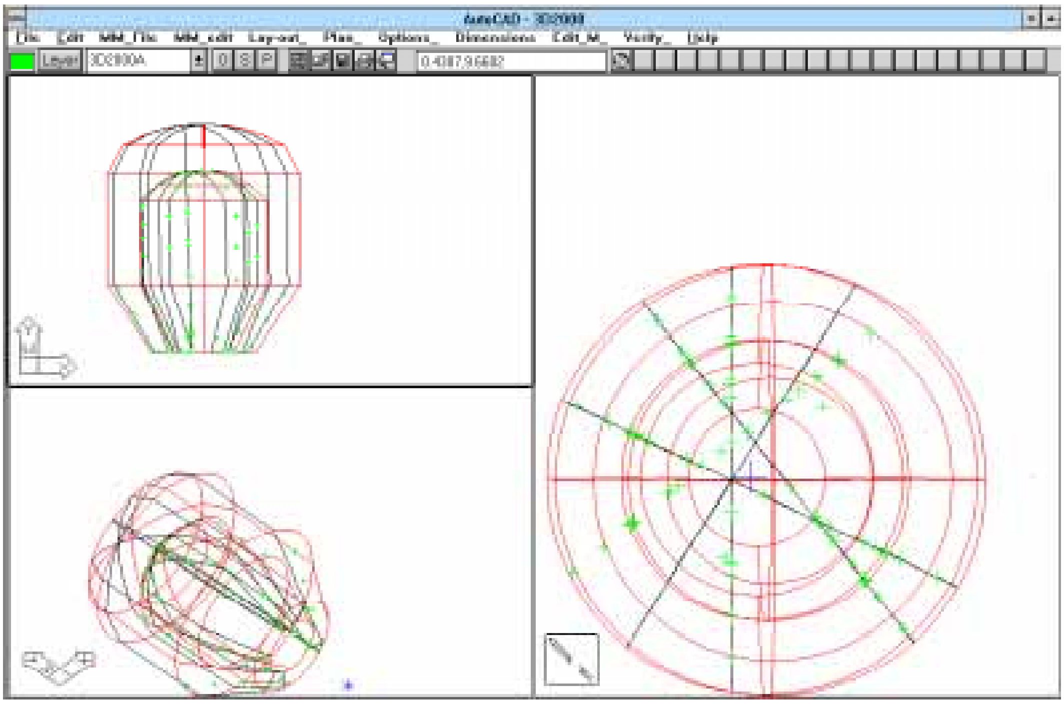

Figure 10. A view point planning screen for converter measurement.

4.2 VISION-GUIDED OPTICAL CO-ORDINATE METERS

Two experimental systems were designed for demonstrating and testing the concept of vision-guided optical co-ordinate measurement. The first[5] was based on the Acman 200 automatic co-ordinate meter (Prometrics 1993b, Acman Systems 1995) and the second[6] on the LR 2000 laser profiler (Rautaruukki 1990, Spectra-Physics VisionTech 1996). Both measurement instruments are angle-angle-range systems using the laser time-of-flight rangefinding technology based on the work done at the University of Oulu on the measurement of very short time intervals (Myllylä 1976) and optical rangefinding (Ahola 1987, Kostamovaara 1987).

The primary requirement for vision guidance is the ability to guide the laser co-ordinate measurement to the desired points with sufficient accuracy, speed and robustness. The co-ordinate meter-based experimental system had following performance goals (Paper VI):

- Reliability: 99.5 % of measurements should succeed
- Target pointing accuracy: 0.025 mRad (0.25 mm at a distance of 10 m)
- Speed: pointing and 3D measurement in 7 s

The performance goals for the laser profiler-based experimental system were set by comparing them with the current manual solution, which should be improved:

[5] This system is referred to as the co-ordinate meter-based experimental system.

[6] This system is referred to as the laser profiler-based experimental system.

- ❏ To improve the repeatability of the co-ordinate system set-up. Current implementation has RPDE < 0.5%. (The Reference Point Distance Error, RPDE, is the difference between the model and the current measured distances between reference points.)
- ❏ To reduce the probability of human error.
- ❏ To minimise the use of expensive process time from the current level of 40 - 120 s depending on the operator.

4.2.1 Implementation of vision guidance

The implementation of the two vision-guided experimental systems is described here. Both systems employ similar computer vision algorithms and use the control methods discussed in Chapter 3.2.

Image analysis methods for finding artificial targets and natural features were implemented for the experimental systems. Artificial targets, their properties and computer vision methods for locating them are discussed in detail in Paper VI. An approach using a template matching method for coarse location of a retro-reflective circular target and a centroid method for exact location were implemented. A normalised correlation method was used for locating arbitrary natural patterns and pointing at them, see Paper VII.

The Acman 200 automatic co-ordinate meter (Prometrics 1993b), on which the first experimental system was based, is designed for dimensional control applications requiring mm-level accuracy and a measurement range of up to 15 m. The prototype of the Acman 200 is described in more detail in Paper III, its application to shipyard measurements is discussed in Paper IV and an application with prefabricated elements is reported by Heikkilä (1996).

The high-level control system of the co-ordinate meter-based experimental system was redesigned and implemented in such a way that the measurement instrument was able to execute measurement sequences automatically according to the MMF and to operate under vision guidance. The control system was implemented as a Windows software application comprising a graphical user interface for evoking automatic MMF operation and manual operations and software for interpreting and executing MMFs. The software resides in a PC, which also contains the frame grabber for the vision system. The PSD-based Target Aiming Sensor (Mäkynen et al. 1994) and the associated pointing system were replaced with a vision sensor installed on the same optical axis as the rangefinder. A schematic diagram of this experimental system is shown in Figure 11 and a photograph in Figure 12, in which the co-ordinate meter with computer-controlled light source is in the middle, the control system user interface in the screen on the right, a captured image with a retro-reflective target and graphical overlay in the other screen and a case with the co-ordinate meter electronics in the back. The PC for the control system is not shown in the photograph. A more detailed description of the co-ordinate meter-based experimental system can be found in Papers V and VI.

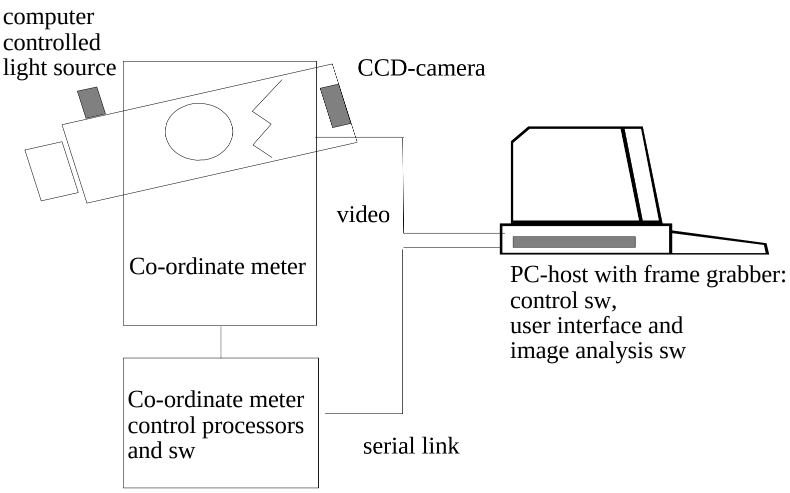

Figure 11. Schematic diagram of the co-ordinate meter-based experimental system.

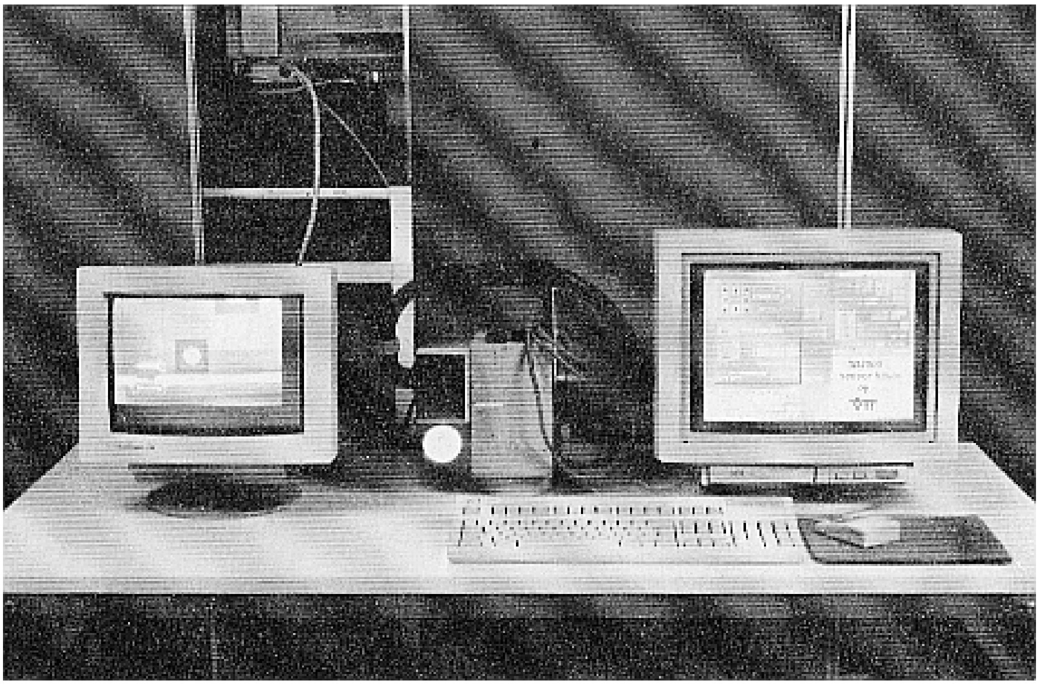

Figure 12. The co-ordinate meter-based experimental system (adapted from Paper V).

The LR 2000 laser profiler is designed for refractory lining wear monitoring at steel mills (Rautaruukki 1990), and is able to measure hot linings (1400°C) from distances of up to 30 m with an accuracy better than 10 mm (Määttä et al. 1993). The laser profiler can be pre-programmed to perform measurement sequences automatically by pointing at the limits of the scanning area.

On account of its existing pre-programming facility and the fact that the vision guidance was mainly used for one function, setting up the co-ordinate system, the control software of the experimental system required only moderate changes. It was modified to incorporate the vision system as a sensor replacing manual pointing in the co-ordinate system set-up. The MMFs were not used with the laser profiler-based experimental system, but instead a data file containing the nominal locations of the co-ordinate system set-up points was used.

The laser profiler-based experimental system was equipped with a separate vision PC and vision sensor. The separate PC could be replaced later with a frame grabber with a certain processing power, but its presence was justified in the development stage by its possession of convenient development and debugging tools. The vision sensor, i.e. a video camera, was attached to the measurement head in an off-axis configuration with the range measurement optics, as shown in the schematic diagram of Figure 13. The laser profiler-based experimental system is shown in Figure 14, in which the laser profiler with the video camera is seen on the right, the vision PC with user interface in the middle and the video monitor on the left. Because of the off-axis configuration, the vision sensor and measurement head must be calibrated. The calibration equations, based on the pin hole camera model, are explained in Paper VII.

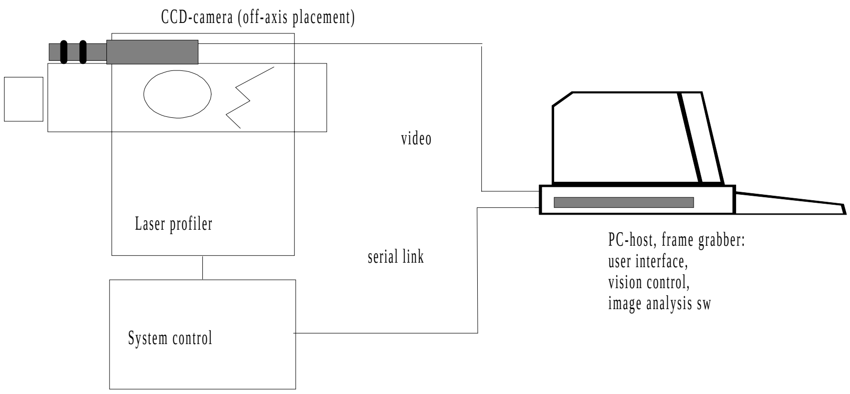

Figure 13. Schematic diagram of the laser profiler-based experimental system.

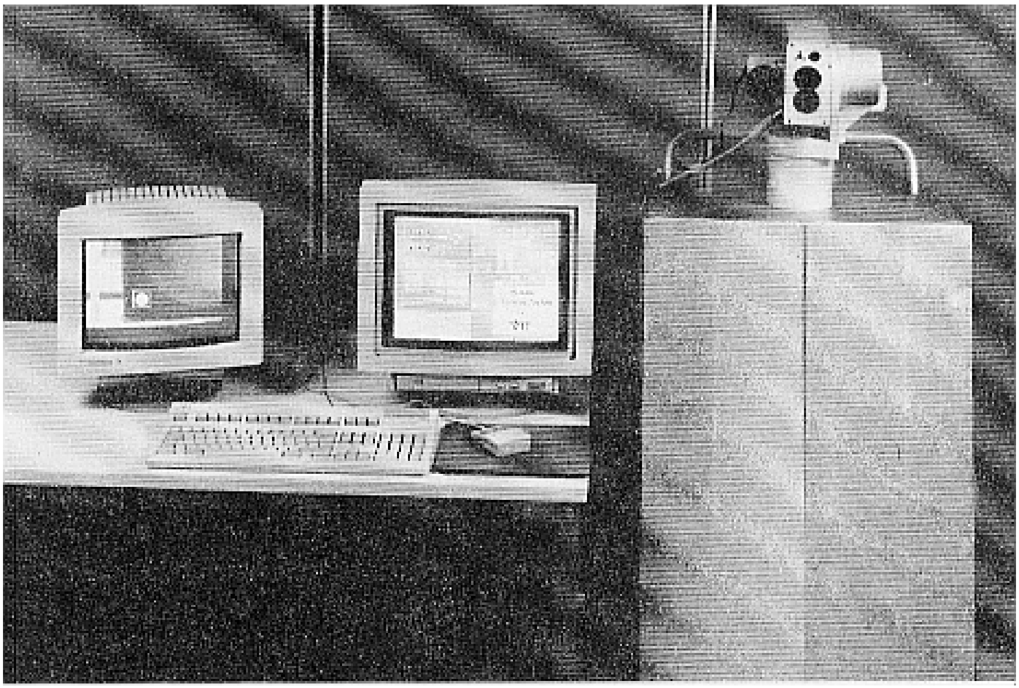

Figure 14. The laser profiler-based experimental system (adapted from Paper VII).

4.2.2 Experimental results

The performance of the two vision-guided experimental systems was evaluated in terms of pointing repeatability, accuracy, reliability, stability and execution time and compared with the design goals. A short summary of the measurement set-up, measurements and their analysis is given here. The performance measurements and results are described in detail in Papers VI and VII. Some early results are also reported by Ailisto et al. (1994).

The performance tests for the co-ordinate meter-based experimental system were carried out in a large hall at VTT Electronics using the reference co-ordinate system maintained there. The automatic measurement sequence was controlled by a MMF produced with the measurement planning tool, see Chapter 4.1. Seven reference points marked with circular retro-reflective and matt targets were measured 60 times from measurement distances varying between 4.5 m and 16 m. The results are summarised in Table 2 together with the design goals.

Table 2. Performance factors of the vision guidance of the co-ordinate meter-based experimental system.

Performance factor	Actual	Design goal
Pointing repeatability Pointing accuracy	0.019 mRad (pan) std. deviation 0.04 mRad (worst case)	0.025 mRad , i.e. 0.25 mm at 10 m
Reliability as a percentage of successful measurements	100%	99.5%
Execution speed	20 s/point	7 s/point for pointing and measurement

When considering the pointing accuracy, it should be noted that the figure given also contains some error inherent in the reference method, namely manual sighting. Bearing this in mind, it can be claimed that the design goal of 0.025 mRad was achieved in most cases. The execution speed was about three times slower than the design goal, however. There are several ways of improving the execution speed, including using partial images and coarser steps in the initial template search. These means were implemented in the vision software and tested with the laser profiler-based experimental system, where significant improvement was achieved, see Paper VII.

The 3D measurement accuracy of the co-ordinate meter-based experimental system was measured and is reported in detail in original paper VI. The seven reference points mentioned above were used and their measured co-ordinate values were compared with reference values measured with a two-theodolite system. After minimising the residuals by six-parameter co-ordinate transformation, 81% of the averaged x, y and z values were within ±1 mm of the reference value. It should be noted that the error figure also contains the uncertainty of the reference point co-ordinates, which is of the order of 0.4 mm (std. deviation).

Similar performance measurements were made with the laser profiler based experimental system. These are described in Paper VII, and a summary of the results is given here. It should be noted that the design goals for the two experimental systems differ markedly in some respects due to their different applications. This is also projected to the relative importance of different performance factors. These factors are summarised in Table 3.

Table 3. Performance factors of the vision guidance of the laser profiler-based experimental system.

Performance factor	**Actual**
Pointing repeatability	0 steps typical, 3 steps maximum (step = 0.4 mRad)
Repeatability of co-ordinate system set-up	RPDE < 0.1% (in laboratory conditions)
Execution speed	0.3 s/point (min), 5 s/point (typical)

4.3 DEMONSTRATION CASES

Two cases drawn from the shipbuilding and steel industries were used to demonstrate the concept of CAD model-based automated 3D measurement.

Curved steel panels are basic components used in the building of ship hulls and their correct shape and dimensions are important for the subsequent assembly stages in order to minimise reworking and adjustment (Storch & Gribskov 1985). This task is seen as an important application of optical 3D measurement in shipyards (Moring et al. 1989). The most interesting geometrical features of a panel are the co-ordinates of its corners, the shapes of its edges and its cross-sections at the points where the stiffeners are welded.

The panel measurement task consists of setting up world and object co-ordinate systems, vision-guided measurement of targeted points along the edges of the plate and non-guided measurement of defined cross-sections in the object co-ordinate frame. The planning session was similar to that described in Chapter 4.1.2, except for the setting up of two separate co-ordinate systems and the planning of the measurement of cross-sections.

The experiment was performed in the VTT hall on a small curved panel (approximately 1.5 m by 1.5 m). A MMF was generated for controlling the execution of the measurements and transferred to the measurement system computer. Automated execution working according to the measurement model was demonstrated successfully and the measured co-ordinate values were saved in a table along with the design values and deviations. This table could be viewed in numerical form using a spread sheet program, for example, or could be used to generate a CAD screen visualising the designed and measured points in different colours. The results can be used to check whether the plate geometry is within the tolerance limits or to guide bending of the plate.

The second demonstration case was drawn from the steelmaking industry (see Paper VII). Converters used in steel making are lined with heat-resistant bricks to a thickness varying from 60 to 100 cm. The lining is typically renewed after 1400 - 1600 heats, at a cost of roughly $350 000. To achieve optimal cost effectiveness, the converter should be used as long as possible without the risk of burn-through. Thus the thickness of the fireproof lining is monitored using laser profiler measurements (Määttä et al. 1993). In spite of the high temperature inside the converter (1100°C - 1400°C) and the rough industrial environment, the measurement system is used routinely, e.g. at Rautaruukki Raahe Steel Mill.

To render the results measured at different times comparable, they must be transformed into the same co-ordinate system using reference points attached to the converter or structures around it. The proper coordinate system set-up is very important for the reliability and accuracy of the measurements, since any errors made in the set-up will be reflected in the subsequent measurements. In the current commercial system, the co-ordinate system is set up by the operator using a telescope to aim at the reference points.

The goals in the converter measurement case were

- ❏ to improve the repeatability of the co-ordinate system set-up and thereby facilitate more accurate wear monitoring, leading to prolonged lining life through the ability to use smaller tolerances without increasing the risk of burn-through,
- ❏ to reduce the probability of human error in the set-up phase,

❑ to minimise the use of expensive process time, and

❑ to eliminate safety hazards and facilitate operation in otherwise non-reachable places

by using vision to automate the co-ordinate system set-up process.

The laser profiler-based experimental system described in Chapter 4.2 and Paper VII was used. The operator pointed the measurement device roughly at the reference points and the vision system then guided the measurement of the reference points using information from a simple geometric model. The operation was first tested successfully in the large hall at VTT Electronics (see Table 3 for performance figures) and then in on-site tests at Rautaruukki Raahe Steel Mill.

The co-ordinate system was set up successfully even in the hostile industrial environment, although the uneven and dynamically changing illumination conditions due to light emitted from the converter and soiling of the reference targets posed problems. The illumination problem was dealt with by using a bright light source to illuminate the target area and by protecting the camera lens from stray-light. The soiling problem was solved by employing a more robust normalised correlation method for locating the target instead of the centroid method. This had the side-effect of prolonging the image processing time. The experimental system containing an extra vision PC communicating with the laser profiler control computer via a serial link proved to be somewhat unreliable in the industrial environment, but this can be corrected in future implementations by integrating the vision system under the direct control of the laser profiler computer. The experimental system as used in the on-site tests is shown in Figure 15.

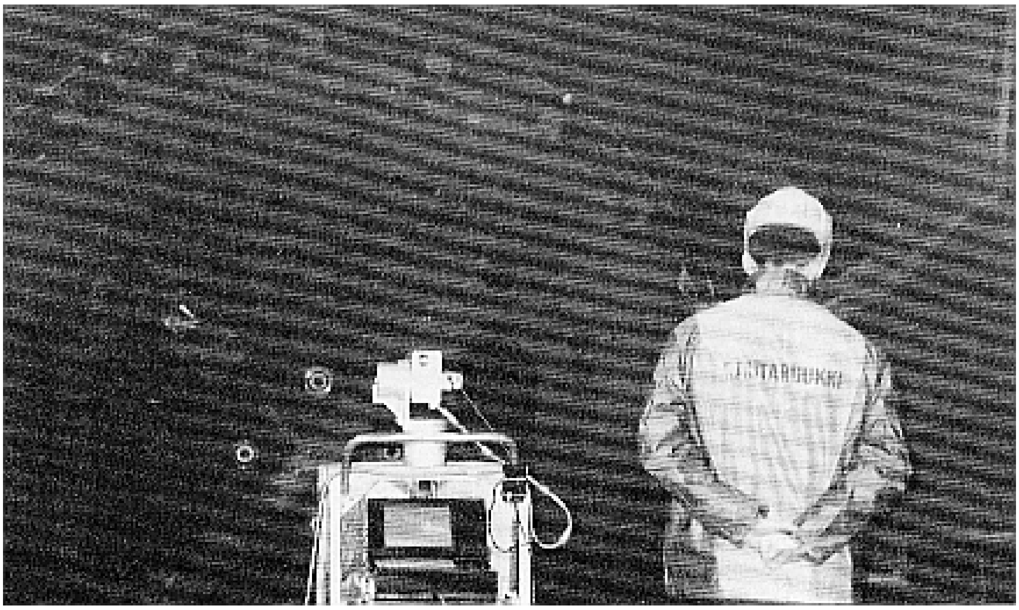

Figure 15. The laser profiler-based experimental system at Raahe Steel Mill.

5 DISCUSSION

The concept of CAD model-based automated 3D measurement was presented in Chapter 3 and its feasibility was evaluated by the experimentation described in Chapter 4. In this chapter the feasibility of the concept is discussed, the needs for future research are outlined and new possible application areas are pointed out.

Automated 3D measurement can be seen as comprising two steps, namely measurement planning and measurement execution. The analysis and use of measured results forms the subsequent step, which was given less emphasis in this work, since the use to which the results are put is very much an application-specific issue.

An interactive approach combining the advantages of both a human designer and a computer was adopted in the CAD model-based measurement planning. This differs from the approach taken by many researchers in this field, who have proposed systems generating measurement plans automatically from CAD descriptions (see Park & Mitchell 1989, Merat & Radack 1992, Yang et al. 1994, Newman & Jain 1995a). Although the automatic approach is interesting and challenging, it tends to limit the flexibility and application domain of the system, since the system must use a lot of *a priori* information. Our interactive approach utilises human knowledge, intelligence, judgement and flexibility as well as the speed and accuracy of the computer in the measurement planning process.

The measurement planning tool was implemented using an industry standard CAD package, ensuring compatibility with an existing CAD data base, a clear difference relative to systems based on experimental CAD software. In addition, this choice had the advantage of providing a documented development environment with a variety of existing functions for handling geometric models and building a user interface.

Experimentation in two cases showed the feasibility of the concept of CAD model-based measurement planning. The measurement planning tool implemented here is able to import industry standard CAD files, and it provides the user with functions for file and view manipulation, measurement area lay-out and co-ordinate system set-up planning, and for the planning of various measurement functions with or without vision control. The tool produces a measurement model file executable by the vision controlled AAR devices used here. Since the measurement planning tool is implemented with the development tools of a widely used commercial CAD package, its user interface is easy for CAD users to adopt and it can be added to existing CAD systems without the extra cost of purchasing CAD software. In this respect it differs from many measurement planning tools proposed in the literature, which are based on experimental CAD systems.

The most evident drawbacks in the current implementation are its sluggish operation in some pointing operations and deficiencies in user friendliness, problems partly related to limitations in the development environment, 3D representations and existing library functions. Other questions related to the use of the measurement planning tool are the cost of the CAD package and updating of the measurement tool when new versions of the CAD package are introduced.

The measurement planning tool is being used and developed further for real-time photogrammetry applications (Oksanen 1996). View point planning as implemented in the tool forms the starting point for product development in the steel mill measurement case. Future development work will show the feasibility of the concept in different application domains.

The measurement plan is conveyed to the measurement system in the form of a Measurement Model File (MMF), which was defined in such a way as to make it readable by both computers and humans. The experimentation showed the feasibility of the solution, as the measurement planning tool was able to produce a MMF automatically from planning decisions made by the operator, and the measurement system control computer was able to execute the instructions coded in the MMF.

The use of sensory feedback to guide 3D measurement is motivated by the need to guide measurement to the right locations in spite of changes in the measurement set-up, object location or geometry. The flexibility gained in this way is regarded as essential for automatic 3D measurement, especially in environments like shipyards and steel mills, which cannot be totally controlled.

Laser radar-based AAR devices, which have been found to be suitable for measuring of large objects and structures (Moring 1995), were used for 3D geometric measurement. Vision can be used with optical co-ordinate meters for finding and pointing at targets or other visible features of points to be measured. The advantage of vision as compared with solutions involving PSD or returned signal strength is that it can be used for finding not only special retro-reflecting targets but also natural features. The use of natural features of the object to be measured as pointing cues has the advantage of removing the work and cost associated with attaching target marks to the object to be measured. This could be crucial for the acceptance of the 3D measurement technology, e.g. for economic reasons. Furthermore, vision can be used for outlier detection prior to the actual 3D measurement, for teleoperation and for special applications such as slag measurement. The main drawbacks of vision are its slower speed as compared with PSD systems and its higher component cost. Also, its robustness needs to be improved, especially when operating under harsh conditions, e.g. at steel mills.

The pointing repeatability and accuracy achieved with the experimental systems were sufficient for the application cases. The pointing accuracy of 0.04 mRad can be compared with results obtained by Mäkynen et al. (1994) using a PSD, see Chapter 2.3.1. The pointing speeds (from 0.3 to 20 s) is significantly slower than that of a PSD system (Mäkynen et al. 1994), but in the same order as that reported by Gottwald (1988). Also the 3D measurement accuracy of approximately ±1 mm achieved with the co-ordinate meter-based experimental system was satisfactory, e.g. for shipbuilding applications.

The experiences gained with the experimental implementations discussed here lead to some suggestions for future implementations of the measurement planning tool and vision guidance. In particular, the alternative implementation approaches mentioned in Chapter 4.1.1, namely programming environments with graphical support or packages for building custom CAD systems, should be considered. The advantages of a custom approach become important if the application domain is well defined, thus requiring less generality in the tool. Also, if the tool is to be a part of a larger system, it is reasonable to integrate it with existing software using the programming languages already employed. New useful features and functions for the measurement planning tool would be tolerancing, warning of excessively steep measurement angles or excessively long measuring distances and estimation of the measurement uncertainty (which was added to the tool for the photogrammetry case (Oksanen 1996)).

The current measurement plan is coded in a custom MMF format, but the generality of the tool and the usability of automatic optical 3D measurement systems would be strengthened significantly if standardisation of measurement plans or programs could be achieved, as with CMMs (Aubin 1987, Merat & Radack 1992). The situation in this field is perhaps not yet mature for standardisation, however.

The use of a special vision PC in the experimental systems was motivated by easier development and debugging as compared with a vision system integrated with the 3D measurement system computer. When considering further development, it would be beneficial to integrate the vision system with the 3D measurement system, since this would lead to a less costly, more compact and more reliable solution. Interesting possibilities are offered by integrated vision systems such as the Imputer (VLSI Vision 1995), which offer the capabilities of a video camera, frame grabber and processor in the same package. Another alternative would be a vision system consisting of a video camera and a frame grabber with a processor for performing the computer vision routines needed.

Although the application examples were drawn from the shipbuilding and steelmaking industries, the concept and its current implementation could be readily applied to other areas in which the geometries of large objects or structures have to be inspected. Such cases can be found in the construction, aerospace and motor vehicle industries. Prefabricated element production (Heikkilä 1996) and industrial building would be potential applications in construction industry, for example. The methods and tools used in interactive CAD-based measurement planning can also be applied to industrial objects of smaller size, but this would call for measurement methods other than time-of-flight laser rangefinding. Possible alternative measurement techniques could include optical triangulation, 2D machine vision and tactile methods.

6 SUMMARY

Control over the geometry of industrial objects is recognised as an important factor affecting manufacturing costs and quality. This control can be achieved by measurements of dimensions and the co-ordinates of vital points, for instance, but measurement planning is needed to ensure that the goals are reached in an efficient manner.

The widespread use of computer aided design and manufacturing has led to a situation in which product geometries are available in electronic form and machines and measurement devices are controlled by computers. At the same time, the design and manufacturing staff are becoming familiar with the use of computer aided techniques in their everyday work. This is opening up a path for developing CAD-based measurement planning systems serving the purposes of geometric control.

The goal of this work was to develop a concept of CAD model-based automated 3D measurement and to demonstrate its feasibility by implementing and testing experimental systems for two cases drawn from industrial needs. Cases from shipbuilding and steel making were considered. The experimental systems employed AAR devices, but the concept is not restricted to these devices.

The concept of CAD model-based automated 3D measurement divides the measurement task into two steps: computer aided measurement planning and automated measurement execution controlled by the measurement plan and sensory feedback. It is assumed that CAD models contain sufficient information on the object geometry for measurement planning. Automation of the measurement planning step is not pursued, since it is seen that the flexibility needed in planning the measurement of complicated and varying industrial objects is achievable only by humans at the moment. Instead, the computer is seen as an advanced design aid, as in computer aided design. In the second step, the measurement plan is executed using sensory feedback to produce the desired geometric information. The subsequent step, only briefly considered in this work, is the utilisation of this information either on-site, for process control, or later on, e.g. for manufacturing accuracy analysis and product certificates.

In order to test the feasibility of the ideas proposed for computer aided CAD model-based measurement planning, an interactive tool was designed and implemented, a widely used commercial CAD software system as its development environment. This decision was motivated by the need to ensure compatibility with existing CAD data. Furthermore, a measurement model file format was defined for conveying the measurement plans to the optical co-ordinate systems.

Auxiliary sensors, methods and software for controlling two motorised AAR devices according to the measurement model and sensory feedback were implemented. The use of AAR devices was motivated by their suitability for controlling the geometry of large industrial objects and their ability to operate in hostile environments, requirements imposed by the industrial cases considered in this work. The auxiliary feedback sensor used with the AAR devices was a vision system. Vision was regarded as a suitable sensor modality to support laser rangefinder devices since both can operate over a wide range of measurement distances.

The feasibility of the concept of automated 3D measurement was demonstrated by following the whole operation chain of the system from measurement planning to comparison between as-measured and as-designed values in examples involving planning the measurement of targeted points in a large hall, measurement of a curved shell plate used in shipbuilding and view point planning for refractory lining monitoring measurements. The operating principle was found to be sound, but certain limitations emerged, some of which were due to features of the CAD system. Further work with measurement planning tools is required, e.g. in order to improve their user interface and to incorporate tolerancing in measurement planning.

The key performance figures of the co-ordinate meter-based experimental system were a pointing repeatability of 0.019 mRad (std. deviation), a 3D measurement repeatability of 0.3 mm (std. deviation), a pointing accuracy of 0.04 mRad (worst case), a 3D measurement accuracy better than 1 mm for x, y and z in 81% of cases, a reliability as a percentage of successful measurements of 100% and an execution speed of 20 s/point. These results were achieved in an experimental case using measurement distances from 4.5 to 16 m. The results fulfilled the goals set, except for measurement speed, but means for improving that are known.

The laser profiler-based vision-guided experimental system performed well in the co-ordinate system set-up task by comparison with its manual counterpart. The vision-guided operation was significantly faster and the results showed less variation than with manual operation. Experiments carried out at the steel mill indicated that the current implementation was feasible, though improvements in the speed and robustness of the system are needed.

Some of the ideas and solutions developed in this work are already being utilised by industrial companies. Vision is being used for co-ordinate system set-up in a laser profiler-based measurement application in steel manufacturing and development work in this field is continuing. Work on the measurement planning tool is also going on, and the tool is being adapted for photogrammetry applications.

REFERENCES

Acman Systems Ltd. 1995. Acman 200, Automatic 3D co-ordinate meter. Product information.

Ahola, R. 1987. A pulsed time-of-flight laser range finder for fast, short-range, high resolution applications. Oulu: University of Oulu. 53 p. + app. (Acta Universitatis Ouluensis, Series C Technica, no. 38.) ISBN 951-42-2329-2.

Ailisto, H., Mitikka, R., Moring I. & Kaisto, I. 1994. Guiding 3D coordinate measurement with integrated video camera. In: El-Hakim, S. (ed.). Videometrics III, Boston, MA, USA, 2 - 4 November 1994. SPIE vol. 2350. Pp. 100 - 107. ISBN 0-8194-1685-1.

Arman, F. & Aggarwal, J. K. 1993a. Model based object recognition in dense-range images - a survey. ACM Computing Surveys, vol. 25, no. 1, pp. 5 - 43. ISSN 0360-0300.

Arman, F. & Aggarwal, J. K. 1993b. CAD-based object recognition in range images using pre-compiled strategy trees. In: Jain, A. K. & Flynn, P. (eds.) Three-Dimensional Object Recognition Systems. Amsterdam: Elsevier. Pp. 115 - 134. ISBN 0 444 89797 6.

Aubin, R. 1987. Dimensional measuring interface specification. In: McKee, K. (ed.). Proc. of 8th International Conference on Automated Inspection and Product Control. Chicago, 23 - 25 June 1987. IFS Ltd. Pp. 25 - 32. ISBN 0-9948507-54-3.

Besl, P. 1988. Active optical range imaging sensors. Machine Vision and Applications, vol. 1., no. 2, pp. 127 - 152. ISSN 0932-8092.

Bhanu, B. & Ho C.-C. 1987. CAD-based 3D object representation for robot vision. IEEE Computer, vol. 20, no. 8, August 1987, pp. 19 - 35. ISSN 0018-9162.

Bhanu, B. 1987. CAD-based robot vision. IEEE Computer, vol. 20, no. 8, August 1987, pp. 13 - 16. ISSN 0018-9162.

Boulanger, P. 1993. Reverse engineering of complex surfaces based on a new hierarchical segmentation method. In: El-Hakim, S. (ed.), Videometrics II. Boston, MA, USA, 7 - 10 September 1993. SPIE vol. 2067. Pp. 186-197. ISBN 0-8194-1332-1.

Bowyer, K. 1992. Special issue on directions in CAD-based vision. CVIGP: Image Understanding, vol. 55, no. 2, pp. 107 - 108. ISSN 1049-9660.

Bradley, C. & Vickers, G. 1993. Free-form surface reconstruction for machine vision rapid prototyping. Optical Engineering, vol. 32, no. 9, pp. 2191 - 2200. ISSN 0036-1860.

Cielo, P. 1988. Optical Techniques for Industrial Inspection. Academic Press Inc. San Diego, USA. 606 p. ISBN 0-12-174655-0.

Critchlow, A. 1985. Introduction to Robotics. New York: Macmillan Publishing Company. 491 p. ISBN 0-02-325590-0.

Dhond, U. & Aggarwal, J. 1989. Structure from stereo - a review. IEEE Transactions on Systems, Man and Cybernetics, vol. 19, no. 6, pp. 1489 - 1510. ISSN 0018-9472.

Disc Software Inc. 1994. Product information. TG-CAD, CAD/CAM/CAE programming engine.

Driels, M. & Pathre, U. 1991. Vision-Based Automatic Theodolite for Robot Calibration. IEEE Transactions on Robotics and Automation, vol. 7, no. 3, pp. 351 - 360. ISSN 1042-286X

El-Hakim, S., Burner, A. & Real, R. 1989. Video Technology and Real-Time Photogrammetry. In: Karara, H. (ed.), Non-Topographic Photogrammetry, Second edition. Falls Church, Virginia, USA: American Society for Photogrammetry and Remote Sensing. Chapt. 17. Pp. 279 - 302. ISBN 0-944426-10-7.

El-Hakim, S., Pizzi, N. & Westmore, D. 1992. The VCM automated 3-D measurement system - theory, application and performance evaluation. In: Bowyer, K. (ed.). Applications of Artificial Intelligence X: Machine Vision and Robotics, Orlando, FL, USA, 20 April 1992. SPIE vol. 1708. Pp. 460 - 482. ISBN 0-8194-0873-5.

ElMaraghy, H. & Gu, P. 1987. Expert System for Inspection Planning. Annals of the CIRP, vol. 36, no. 1, pp. 85 - 89. ISSN 0007-8506.

Feng, S. 1994. Dimensional Inspection Planning Based on Product Data Standards. In: Paul, A. & Sobolewski, M. (eds.). Proceedings of Concurrent Engineering: Research and Applications. Pittsburgh, USA, 29 - 31 August 1994. Johnstown, PA, USA: Concurrent Technologies. P. 333 - 342. ISBN 0-9642449-0-X.

Flynn, P. & Jain, A. 1991. CAD-based computer vision: from CAD models to relational graph. IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 13, no. 2, pp. 114 - 132. ISSN 0162-8828.

Fraas, K.-Ch., Giese, U. & Kamsties, K.-D. 1991. Combined photogrammetry and 3-D CAD for plant documentation and planning of refits. Kerntechnik, vol. 56, no. 3, pp. 174 - 177. ISSN 0932-3902.

Gottwald, R. & Berner, B. 1987. The new KERN System for Positioning and Coordinate Determination. In: Technical Papers 1987 ACSM-ASPRS annual Convention, vol. 3, pp. 260 - 266.

Gottwald, R. 1988. Kern Space: An automated non contact 3-D measuring system for industrial applications. In: Proceedings of the 7th International Conference on Robot Vision and Sensory Controls, Zurich, 2 - 4 February, 1988. Kempston, Bedford, UK: IFS. Pp. 3 - 12. ISBN 0-948507-780.

Graebling, P., Eugène, R., Draman, C. & Hirsch, E. 1992. On-line visual inspection of manufactured parts by comparison of real images and CAD-based representations. Application to Sculptured Surfaces. In: 8th. International Conference on CAD/CAM, Robotics and Factories of the Future. Metz, France, 17 - 19 August 1992. Univ. of Metz. Vol. 2. Pp. 1440 - 1454.

Gremban, K. & Ikeuchi, K. 1993. Appearance-based vision and the automatic generation of object recognition programs. In: Jain, A. K. & Flynn, P. (eds.) Three-Dimensional Object Recognition Systems. Amsterdam: Elsevier. Pp. 229 - 258. ISBN 0 444 89797 6.

Gunnarsson, K. & Printz, F. 1987. CAD model based localization of parts in manufacturing. IEEE Computer, vol 20, no. 8, pp. 66 - 74. ISSN 0018-9162.

Haggrén, H. 1993. Vision system for 3-D car body orientation. In: El-Hakim, S. (ed.). Videometrics, Boston, MA, USA, 15 - 20 November 1992, SPIE vol. 1820. Pp. 132 - 135. ISBN 0-8194-1021-7.

Heikkilä, R. 1996. The applicability of an electro-optical coordinate measuring technique to the dimensional control of precast concrete facade panel production. Oulu: University of Oulu. 87 p. + app. (Acta Universitatis Ouluensis - C Technica 86.) ISBN 951-42-4248-3.

Hirsch, E. 1991. Vision Based Online Inspection of Manufactured Parts: Comparison of CAD and CCD Images. In: Gassilloud, D. & Grossetie, J. (eds.) Computing with parallel Architectures: T.Node. Kluwer Academic Publishers. Pp. 173 - 196. ISBN 0-7923-1225-2.

Hoffman, R., Keshavan, H. & Towfiq, F. 1989. CAD-Driwen Machine Vision. IEEE Transactions on Systems, Man and Cybernetics, vol. 19, no. 6, pp. 1477 - 1488. ISSN 0018-9472.

IGES. 1988. Initial Graphics Exhange Specification IGES Version 4.0. Washington DC: US Department of Commerce, National Bureau of Standards. 515 p.

Jarvis, R. 1993. Range sensing for computer vision. In: Jain, A. & Flynn, P. (eds.). Three-dimensional object recognition systems. Amsterdam: Elsevier. Pp. 17 - 56. ISBN 0 444 989797 6.

Kaarela, K. 1996. Enhancing communication of plant design knowledge. Espoo: Technical Research Centre of Finland. 110 p. + app. 81 p. (VTT Publications 272.) ISBN 951-38-4930-9.

Kahmen, H. 1992. Hochpräzise Zielerfassung durch Roboter theodolite. In: Matthias, H. & Grun A. (eds.). XI Internationaler Kurs für Ingenieurvermessung. Zurich, 21 - 25 September 1992. Bonn: Drummer's Verlag. Pp. II 6/1 - 6/13. (In German.)

Kaiser, J. 1985. Robot-operated body inspection system. In: Nof, S. (ed.) Handbook of Industrial Robotics. New York: John Wiley & Sons. Pp. 1205 - 1208. ISBN 0-471-89684-5.

Kallio-Kokko, H. 1994. Mittausmallin luontia tukeva työkalu. Insinöörityö. Oulu: Oulun teknillinen oppilaitos. 42 p. + app. 57 p. (In Finnish.)

Katowski, O. 1992. Ein Präzisionspolar-Messsystem (PPMS) im Einsatz bei Überwachungsmessungen und dynamischer Absteckung. In: Matthias, H. & Grun, A. (eds.). Ingenieurvermessung 1992. Zurich, 21 - 25 September 1992. Vol. 1. Drummer's Verlag, Bonn, Germany. Pp. II 5/1 - 5/10. (In German.)

Kilpi, V., Larikka, E., Leikas, E. & Björk, H. 1992. Advanced Robotic Seam Sealing Application. Proceedings of 23rd International Symposium on Industrial Robots, Barcelona. Pp. 621 - 625.

Klafter, R., Chmielewski, T. & Negin, M. 1989. Robotic Engineering - An Integrated Approach. Englewood Cliffs, NJ: Prentice-Hall International. 744 p. ISBN 0-13-782053-4.

Kliem, J. 1989. Systemvorstellung der Vollautomatischen motorisierten Totalstationen der Firma Geodimeter. In: Gruen, A. & Kahhmen, H. (eds.). Optical 3-D Measurement Techniques. Vienna, Austria 18 - 20 September 1989. Pp. 404 - 412. ISBN 3-87907-200-0. (In German.)

Koivunen, V. & Vezien J.-M. 1996. Machine vision tools for CAGD. International Journal of Pattern Recognitiona and Artificial Intelligence, vol. 10, no. 2, pp. 165 - 182. ISSN 0218-0014.

Kostamovaara, J. 1987. Techniques and devices for positron life-time measurements and time-of-flight laser rangefinding. Oulu: University of Oulu. 69 p. (Acta Universitatis Ouluensis, Series C Technica, no. 37.) ISBN 951-42-2280-6.

Leinonen, A. 1988. 3D-teollisuusmittausjärjestelmät ja takymetrialaitteiden automaatio. Maanmittaus, no. 2/1988, pp. 140 - 153. (In Finnish.) ISSN 0047-5319.

Ley, D. & Becker, M. 1992. Intensity-guided laser range-finding for three-dimensional coordinate-measurement and object-recognition. In: Schenker, P. (ed.). Sensor Fusion V. Boston, MA, USA, 15 - 20 November, 1992. SPIE vol. 1828. Pp. 488 - 498. ISBN 0-8194-1029-2.

Littleworth, R., Stirling, D. & Chandler, J. 1992. Three-dimensional mapping and as-built computer modelling by analytical photogrammetry. International Archieves of Photogrammetry and Remote Sensing, vol. XXIX, part B5, comission V. Pp. 754 - 760. ISSN 0256-1840.

Luhmann, T. 1990. Integrated system for real-time and on-line applications in industrial photogrammetry. In: Gruen, A. & Baltsavias, E. (eds.). Close-Range Photogrammetry Meets Machine Vision, Zurich Switzerland, 3 - 7 September 1990, SPIE vol. 1395, part I, pp. 488-495. ISBN 0-8194-0441-1.

Maas, H.-G. & Kersten, T. 1994. Digital close-range photogrammetry for dimensional checking and control in shipyard. In: El-Hakim, S. (ed.). Videometrics III, Boston, MA, USA, 2 - 4 November, 1994. SPIE vol. 2350. Pp. 108 - 114. ISBN 0-8194-1685-1.

Manninen, M. & Jaatinen, J. 1992. Productive Method and System to Control Dimencional Uncertainties at Final Assembly Stages in Ship Production. Journal of Ship Production, vol. 8, no. 4, pp. 244 - 249. ISSN 8756-1417.

Mason, S. & Gruen, A. 1994. Automating the sensor placement task for accurate dimensional inspection. In: Kak, A. & Ikeuchi, K. (eds.) Second CAD-based Vision Workshop. Champion, PA, USA, 8 - 11 February, 1994. IEEE Computer Society. Pp. 142 - 150. ISBN 0-8186-5310-8.

Menq, C.-H., Yau, H.-T. & Wong, C.-L. 1992a. An Intelligent Planning Environment for Automated Dimensional Inspection Using Coordinate Measuring Machines. Transactions of the ASME, vol. 114, no. 2, pp. 222 - 230. ISSN 1050-0472.

Menq, C.-H., Yau, H.-T. & Lai, G.-Y. 1992b. Automated precision Measurement of Surface Profile in CAD-Directed Inspection. IEEE Transactions on Robotics and Automation, vol. 8, no. 2., pp. 268 - 278. ISSN 1042-296X.

Merat, F. & Radack, G. 1992. Automatic inspection plannig within a feature-based CAD system. Robotics and Computer Integrated Manufacturing, vol. 9, no. 1, pp. 61 - 69. ISSN 0736-5845.

Moring, I. 1995. Laser radar-based range imaging with applications in shape measurement and machine control. Espoo: Technical Research Centre of Finland. 101 p. + app. 69 p. (VTT Publications 220.) ISBN 951-38-4658-X.

Moring, I., Ailisto, H., Koivunen, V. & Myllylä, R. 1989. Active 3-D vision system for automatic model-based shape inspection. Optics and Lasers in Engineering, vol. 10, nos 3 & 4, pp. 149 - 160. ISSN 0143-8166.

Myllylä, R. 1976. On the measurement technique of positron lifetimes. Oulu: University of Oulu. 72 p. (Acta Universitatis Ouluensis, Series C Technica, no. 10.) ISBN 951-42-0343-7.

Määttä, K., Kostamovaara, J. & Myllylä, R. 1993. Profiling of hot surfaces by pulsed time-of-flight laser range finder techniques. Applied Optics, vol. 32, no. 27, pp. 5334 - 5347. ISSN 0003-6935.

Mäkynen, A., Kostamovaara, J. & Myllylä, R. 1994. Tracking laser radar for 3-D shape measurements of large industrial objects based on time-of-flight laser rangefinding and position-sensitive detection techniques. IEEE Transactions on Instrumentation and Measurement, vol. 43, no. 1, pp. 40 - 48. ISSN 0018-9456.

Newman, T. & Jain, A. 1995a. A System for 3D CAD-based inspection using range images. Pattern Recognition, vol. 28, no. 10, pp. 1555 - 1574. ISSN 0031-3203.

Newman, T. & Jain, A. 1995b. A Survey of Automated Visual Inspection. Computer Vision and Image Understanding, vol. 61, no. 2, pp. 231 - 262. ISSN 1077-3142.

Oksanen, K. 1996. The design and simulation of video digitising using three-dimensional CAD-models. In: Kraus, K. & Waldhäusl, P. (eds.). International Archieves of Photogrammetry and Remote Sensing. ISPRS vol. XXXI, part B5, pp. 432 - 437. ISSN 0256-1840.

Park, H. & Mitchell, O. R. 1989. Automated Computer Vision System for Quick Turnaround Machining. In: Chen, M. (ed.). Automated Inspection and High Speed Vision Architectures II. Cambridge, MA, USA, 10 - 11 November 1988. Bellingham, WA, USA: SPIE vol. 1004. Pp. 114 - 125. ISBN 0-8194-0039-4.

Pettersen, A. 1992. Metrology Norway system - an on-line industrial photogrammetry system. In: Fritz, L. (ed.). International Archives of Photogrammetry and Remote Sensing. Washington DC, USA: ISPRS vol. XXIX, part B5. Pp 43 - 49.

Prometrics Ltd. 1993a. Acman 1000, 3D dimensional control system. Product information.

Prometrics Ltd. 1993b. Acman 200, Automatic 3D co-ordinate meter. Product information.

Rautaruukki Oy. 1990. LR-2000 laser profiler. Product information.

Schwartz, D. 1989. Vision Metrology System: An automated noncontact three-dimensional measurement system. In: ASPRS/ACSM Annual Convention. Vol. 1. Pp. 145 - 156.

Sormunen, J. 1986. Valmistustarkkuuden seuranta ja ohjaus laivan runkorakentamisessa. Diploma Thesis. Lappeenranta: Lappeenranta University of Technology. 98 p. (In Finnish.)

Spectra-Physics VisionTech Oy. 1996. LR-2000 laser profiler. Product information.

Storch, R. & Gribskov, J. 1985. Accuracy control for U.S. Shipyards. Journal of Ship Production, vol. 1, no. 1, pp. 64 - 77. ISSN 8756-1417.

Stürmer, B. & Stegmaier, E. 1989. Different Solutions for CAD Data Based Offline Programming of Coordinate Measuring Machines in the Quality Assurance Department of Volkswagen AG, Braunschweig. In: IMEKO-Symposium - Dimensional Metrology in Production and Quality Control. Aachen, Germany, 20 - 22 September 1989. VDI Verlag. Pp. 323 - 329. (VDI Berichte 761.) ISBN 3-18-090761-4.

Tarbox, G. & Gottschlich, S. 1995. Planning for complete sensor coverage in inspection. Computer vision and image understanding, vol. 61, no. 1, pp. 88 - 111. ISSN 1077-3142.

Teeuw, W., Liefting, J., Demskes, R. & Houtsma, M. 1995. Product Data Interchange in Practise: Experiences, Problems and Opportunities. In: Paul, A. & Sobolewski, M. (eds.). Proceedings of the Concurrent Engineering 1995 Conference, McLean, Virginia, 23 - 25 August, 1995. Johnstown, PA: Concurrent Technologies Corporation. Pp. 1 - 11. ISBN 0-99642449-1-8.

Topcon Corporation. 1992. AP-S1 Autotracking total station. Product information.

VLSI Vision Ltd. 1995. Imputer 2. Product information.

Weiqian, L., Quangwen, K. & Tianning, X. 1990. Determination of the deformation of the bridge model in real time with CCD solid state camera. In: Gruen, A. & Baltsavias, E. (eds.). Close-Range Photogrammetry Meets Machine Vision. Zurich, Switzerland, 3 - 7 September, 1990. Bellingham, WA, USA: SPIE vol. 1395. Pp. 1181 - 1188. ISBN 0-8194-0441-1.

Yang, C., Marefat, M. & Kashyap, R. 1994. Active Visual Inspection Based on CAD Models. In: Proceedings of IEEE International Conference on Robotics and Automation. Los Alamitos, USA. IEEE Computer Society Press. Vol. 2. Pp. 1120 - 1125.

Yau, H.-T. & Menq, C.-H. 1990. The development of an Intelligent Dimensional Inspection Environment in Manufacturing. Proceedings of 1990 Japan - U.S.A. Symposium on Flexible Automation - A Pacific Rim Conference. Kyoto, Japan, 9 - 13 July, 1990. Kyoto: ISCIE. Vol. 3. Pp. 1059 - 1065.

Yau, H.-T. & Menq, C.-H. 1992. An automated dimensional inspection environment for manufactured parts using coordinate measuring machines. International Journal of Production Research, vol. 30, no. 7, pp. 1517 - 1536. ISSN 0020-7543.

Yi, J. & Chelberg, D. 1994. Rapid object recognition from a large model database. In: Kak, A. & Ikeuchi, K (eds.) Proceedings of Second CAD-based vision workshop. Champion, PA., 8 - 11 February 1994. IEEE Computer Society Press. Pp. 28 - 35. ISBN 0-8186-5310-8.

Yuuzaki, M. & Okumato, Y. 1992. An approach to a new ship production system based on advanced accuracy control. In: NSRP Ship Production Symposium. New Orleans, USA, 2 - 4 September 1992. Jersey City: The Society of Naval Architects and Marine Engineers. Pp. 7A1-1 - 7A1-10.

Zhou, G. 1986. Accurate determination of ellipse centres in digital imagery. Technical Papers. ACSM-ASPRS Annual Convention, vol. 4. Pp. 256 - 264.

Appendices of this publication are not included in the PDF version.
Please order the printed version to get the complete publication
(http://www.inf.vtt.fi/pdf/publications/1997/)