The Programmable Optical 3D Measuring System POM - Applications and Performance

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ABSTRACT

POM is a programmable 3D multi-sensor measuring system for non-contact optical measurements of points and elements by digital image processing and close-range photogrammetry. The system was initially developed for use in the automobile industry. Due to its unique open system architecture, an integrated database and program interpreter, it can easily be adapted to a large variety of applications.
The system is able to work with different imaging sensors, e.g. reseau-scanning cameras, CCD cameras and video theodolites. A digital rotary table and a number of different light sources may be integrated.
The control software package is based on UNIX and X-Windows/Motif. It consists of the main modules: graphical user-interface, SQL-based database, C-like program interpreter, 3D calculation programs and bundle adjustment, sensor control and image processing.
With suitable sensor and light configurations it is possible to measure a variety of parts made of different materials, e.g. sheet-metal, rubber tubing, glass windshields, plastic objects etc. The powerful element-measuring algorithm enables the direct determination, by multi-image matching, of geometric ~~elements such as~~ circles, cylinders and lines in 3D space. Measurements can either be performed in manual mode (teach-in) or in automatic mode, where the interpreter processes complete measurement program files which are created by the internal program generator.
The paper presents the current development status and describes the measurement of different objects types. Accuracy and speed of the system will also be discussed.

Key Words: on-line photogrammetry, 3D vision, image processing, industrial metrology, quality assurance

1. INTRODUCTION

In the past few years, the technical development in photogrammetry, with the availibility of low-cost powerful computer systems, high-resolution electro-optical imaging sensors and image processing algorithms for pattern recognition and surface measurement, has led to the development of close-range photogrammetric systems for on-line and real-time applications.

The main field of applications is in the industrial environment. Existing machine vision systems normally provide 2D image processing and analysis and are widely used in a large number of industrial applications. However, there are also a few commercial systems, which are more or less designed for specific sensors or applications and which are only used in a limited number of applications [e.g. El-Hakim 1986, Haggrén & Leikas 1987, Grün 1987, Metronor 1990, AICON & VW 1991]. In Addition there is a large number of manual and automated theodolite systems which are mainly used for larger objects in industry [Staiger 1992].

This report presents the result of a joint development between Leica (former Kern) and Rollei in co-operation with several academic institutes. A first version of the Programmable Optical Measuring System (POM) is in use at Volkswagen's R&D department (Fig. 1).

2. REQUIREMENTS

2.1 Specifications

The initial application at the start of development was the 3D measurement of second-source parts which had to be checked for a correct fit into the car body. The conventional solution of this task is manual inspection using expensive, object-specific mechanical gauges [Hegelmann 1989]. The range of components that shall be measured by the system is characterized by very different features of shape, size, surface materials and measuring tasks. The major tasks are measurements of holes, edges, corners, diameters, distances and a variety of special object parts. These features can mainly be described by regular mathematical elements such as circles, lines and cylinders in 3D space.

A system accuracy of ±0.1mm (95%) in an object space of 2.0m x 2.0m x 0.6m is required (1:20'000) and has to be verified with distance measurements. A detailed investigation of accuracy is given in [Godding & Luhmann 1992].

Due to internal changes of quality philosophies the customer has shifted the responsibility for good quality to the second-source manufacturers. This has led to the new situation in which, instead of large series inspections, these parts will only be checked selectively with respect to specific problems that might occur during manufacturing process. Nevertheless the system flexibility must be very high.

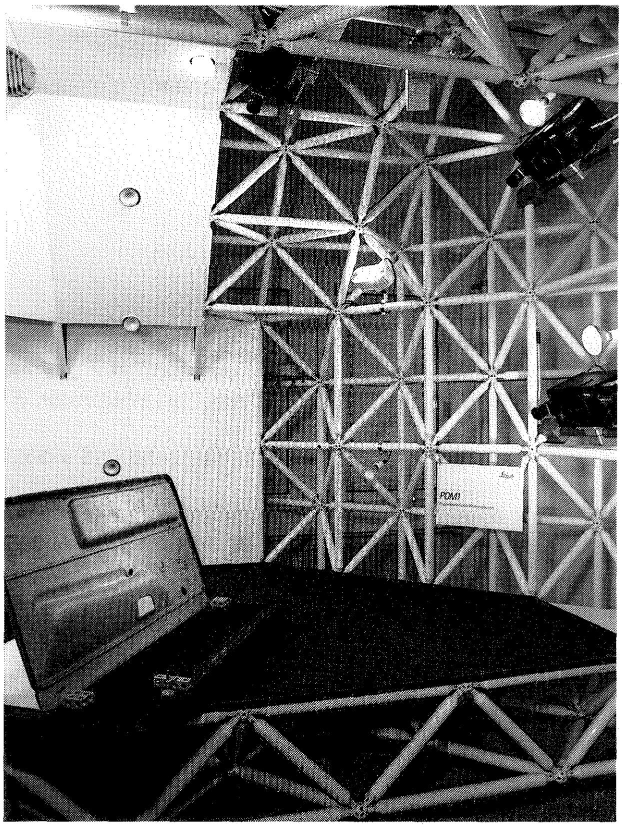


Fig. 1. POM prototype,Volkswagen version

2.2 Solution

The main feature of POM is its modular concept both for hardware and software components. It is implemented in a UNIX workstation and enables an almost free configuration of different sensors. The software system consists of modules for image processing and sensor control, routines for analytical photogrammetry and 3D element calculation, database management and a graphical user-interface. The whole system is internally controlled by a program interpreter which executes the commands of a special programming language.

The complete system is designed such that fast adaptation to new applications can easily be done without changing software source code.

3. Sensor Technology

POM enables the almost free configuration of different sensors and light sources in order to meet the requirements of a specific application. Currently the following sensors can be used:
- Rollei Reseau-Scanning Camera RSC
- CCD video cameras
- Digital rotary table
- Light sources

The RSC offers a large image format (50 x 50mm²) and high resolution (~4000 x 6400 pixels) by sequential object scanning using a standard CCD array sensor [Luhmann & Wester-Ebbinghaus 1986]. It is the only digital metric camera which has focus capability without affecting the interior orientation [Riechmann 1990]. This camera is equipped with a wide-angle CCD camera for overview purposes, which has a field of view similar to the total image format of the RSC. The image of the overview camera can be used for approximate sensor positioning of the RSC (Fig. 2). Camera control is performed by serial interfacing, image information is transferred as analog video signals.

The digital rotary table (Fribosa) serves as an object carrier and enables a flexible positioning of the object with respect to the cameras in order to achieve object surveys from all around. The chosen table has an absolute angle measuring device. The objects are fixed on the table using an off-the-shelf part mounting system.

In order to solve the complex measuring tasks it is necessary to operate with a flexible illumination concept where light intensity and direction can be chosen appropriate to the specific object part which has to be measured. Currently there are up to 32 direct light spots, three diffuse light groups and an integrated light table which all can be controlled by the computer.

In addition to photogrammetric procedures, the use of angle-measuring devices (motorized theodolites, laser-pointers) is anticipated by the system design and is currently under development.

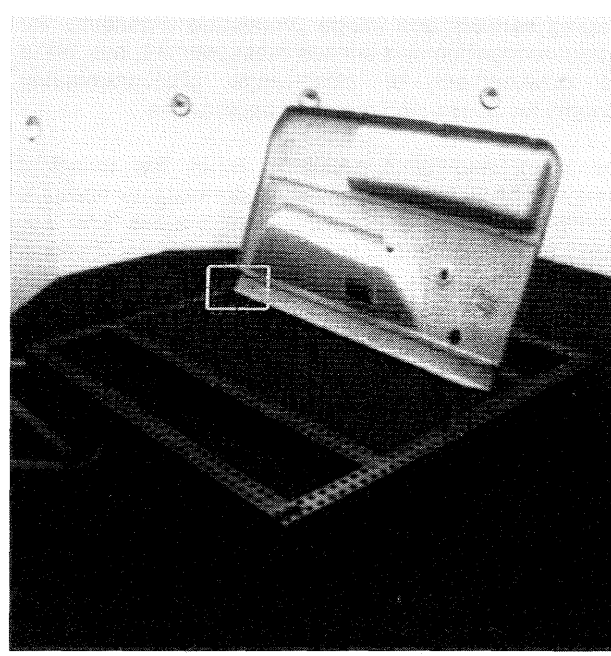


Fig. 2. Overview image for RSC positioning

4. Photogrammetric Methods

4.1 System Configuration

Fig. 1 shows the system configuration of the VW installation. A steel frame of high stability is used to hold three RSCs in a vertical plane. With a mean image scale of 1:30 a partial RSC frame covers an object area of ~100mm x 150mm (1 pixel ≈ 0.2mm x 0.3mm). Using a 60mm lens the resulting measuring volume is about 1.6m x 1.6m x 0.5m. The size of object space can be enlarged using a 47mm lens.

4.2 System Calibration

The system calibration consists of two steps. Firstly, the complete camera calibration is performed using a testfield with approximately known targets and a number of calibrated scale bars. Using a self-calbrating bundle adjustment, the parameters of interior and exterior orientation are calculated.

The second step involves the rotary table, which is calibrated and oriented within the machine coordinate system using bundle adjustment again. An RMS error of bundle adjustment of 1.6µm is obtained, leading to a mean error of <0.05mm for object points [Godding & Luhmann 1992].

The photogrammetric calculations are based on use of the orientation parameters as well as the measured angle of the rotary table. In POM it is possible to use any combination of an unlimited number of cameras and turntable rotations in order to obtain three-dimensional object information. It is even possible to use only one camera with different rotations.

4.3 Three-dimensional point determination

The POM system provides the 3D measurement of points (XYZ) and of elements (3D element parameters). The 3D position of an object point is calculated using multi-image intersection in space, while 3D elements (line, circle, cylinder, sphere) are computed using direct element adjustment. All results are reported together with an internal quality value (Sigma 0).

Bundle adjustment (CAP) [Hinsken 1989] and intersection are able to work with any combination of image coordinates and angle information from theodolites.

4.4 Workpiece coordinate system

Local coordinate systems (e.g. CAD system) can be defined using reference points with nominal values in a workpiece coordinate system. Instead of the well-known 3-2-1 procedure, which is used in conventional CMM systems, POM uses a 3D Helmert transformation which can operate with an unlimited number of object coordinates. These points can also be used with only partially known coordinate components (e.g. only X,Z) and they can be associated with individual weights for the computation. This aspect is of special interest for the measurement of partly non-rigid objects where a larger number of less accurate reference points might be given.

5. Measurement and Image Processing Algortihms

5.1 Point Measurement

The 3D measurement of points is based on intersection in space. Corresponding image points are extracted in each image using image processing routines for ellipse-shaped targets (e.g. retro-reflective targets) and laser spots.

5.2 Element Measurement

The algorithm of ANDRESEN and HELSCH is used to compute the 3D parameters of regular mathematical elements [Andresen & Helsch 1990]. In an unlimited number of images the greylevel contour of an element is extracted using sub-pixel line following. These lists of non-corresponding image points are processed in an iterative adjustment program which directly computes the 3D parameters of an element. This algorithm does not require any approximate starting values given by the operator and can also work with uncomplete contours (e.g. only parts of circle).

This method will only be successful if the extracted greylevel contour is identical in each image and if it represents the physical object edge. This requires a flexible illumination system which has to be adjusted carefully for a specific measuring task.

Table 1 summarizes the types of geometric elements which can be measured with the contour algorithm.

Table 1: Geometric Elements of Contour Algorithm

Element	Computed parameters (number)	Measured contour
Circle	center point, radius, normal vector (7)	partial or complete circle edge
Sphere	center point, radius (4)	part of the edge of the sphere (ball)
Line	line point, normal vector (6)	part of the line edge
Cylinder	1 point on axis, normal vector, radius (7)	portions of cylinder surface (visible edge)

6. SYSTEM PROGRAMMING

The complete system is controlled by a Leica program package. Fig. 3 shows the concept of the system with the main software modules and system processes. The system is implemented under UNIX V on a Sun SparcStation.

The concept of POM is based on the idea that the user can generate his own measuring program for a specific application. This program is usually created during the teach-in process where a manual measurement is stored including all parameters for sensor control and calculation processes. This information can be used to generate a measurement program which then can be executed in automatic mode. For this purpose the user operates with four major tools: Graphical user-interface, database, program interpreter and program generator.

6.1 Graphical User-Interface

The graphical user-interface (GUI) is based on X-Windows and OSF-Motif. It serves as major interface between user and system. It provides all state-of-the-art features of modern interfaces such as mouse control, pull-down menus, online help, window technique, multi-tasking, user-dependent layout, different languages etc (Fig. 4).

In manual measurement mode the GUI uses a restrictive menu control that consists of a number of pre-defined actions in order to leave minimum scope for faulty operations. With each action the GUI enters a sequence of correct commands into the program interpreter which then will be executed.

Using the GUI the user does not have to learn the internal programming language of POM.

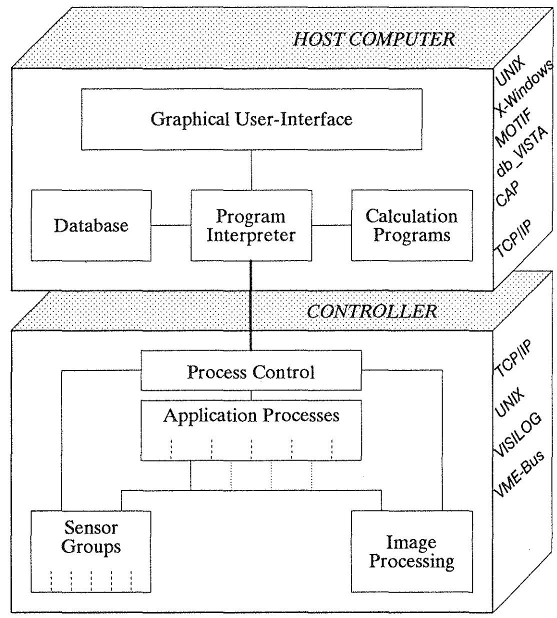


Fig.3 POM software structure

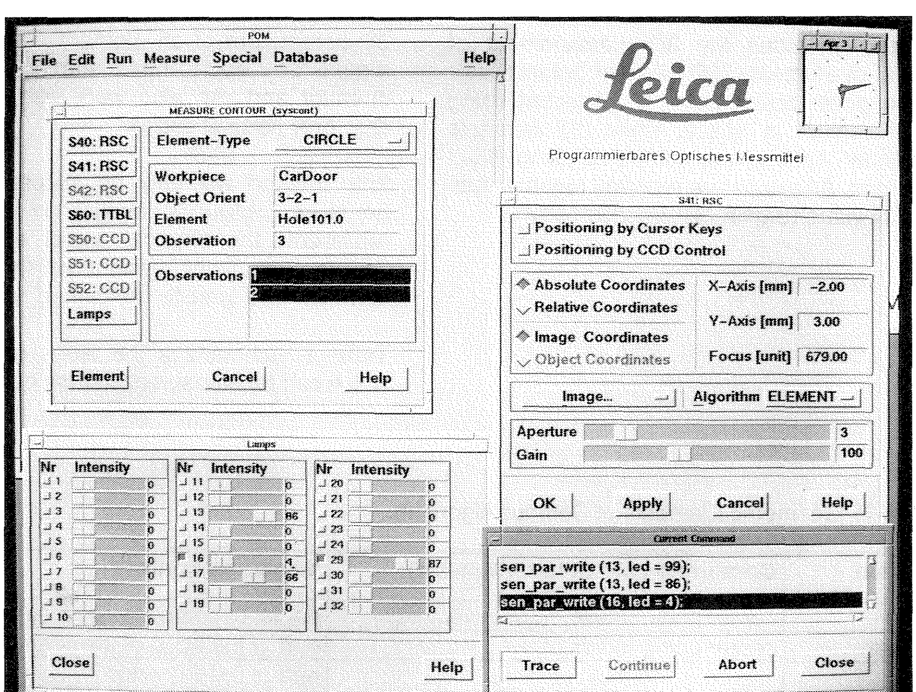


Fig. 4. Graphical user-interface

6.2 Program Interpreter

The program interpreter is the central control unit of the system. It reads program statements, checks for correct syntax and executes them. It synchronizes different tasks and is responsible for a consistent internal system status. The program statements can either be entered via GUI, from existing source files with measuring programs or directly via keyboard input.

The interpreter operates with a special programming language which has programming constructs such as variables, conditional defines, definition of procedures and loops. When executing a command, the interpreter interfaces with the database, calls sensor and image processing functions, executes calculation programs and handles error situations.

Using the GUI it is not necessary to know individual programming statements because all required commands are generated by the system. Advanced programmers can operate the system by direct input of program statements in command mode.

The integrated program generator is able to create optimized measurement programs for single points, elements or complete workpieces. Stored program files can be edited in the bulit-in Motif editor. These files can be executed in automatic mode whereby the operator can stop and continue an automatic process at any time. Fig. 5 shows an example of a measuring program for a circle element measurement.

6.3 Database

All system data such as measurement and calculation results or sensor parameters are stored and managed by a network database (db_Vista). It is based on a data structure that stores a measured element with a unique and reproducable relation to all relevant sensor data and observations. This method is useful to generate a measuring sequence out of the database information at any time.

Two types of elements are managed: a) regular geometric elements as they are computed by the contour algorithm; b) elements which are formed by a number of discrete 3D points (min. 1) belonging to the same object part (e.g. points on a plane or profile).

Repeated measurements for series inspections are stored under the reference element generated in teach-in. While the reference element has a special indicator (0) the following measurments of this element are stored with a higher index. So it is possible to make a statistical analysis of elements.

During measurement, all relevant information is directly stored in the database (on harddisk) in order to maximize data security at risk from unforseen interruptions.

A large variety of database interactions can be performed using SQL (Standard Query Language). As an example, almost any kind of ASCII output format (e.g. CAD interfaces or protocol files) can be generated using SQL programming. The user can write his own SQL programs in order to perform data operations for his specific application.

```
. . . . .
db_put_elem (name = "hole1", index = 1, type = circle);
db_set_elem (name = "hole1", index = 1);
sen_stat_write (4, status = on);
sen_stat_write (10, status = on);
sen_par_write (4, led = 99);
sen_par_write (10, led = 99);
sen_pos_abs (60, hor = 0.00000);
im_cont_init (name = "bohrung", index = 1, type = circle);
db_put_observ (1);
db_set_observ (1);
sen_pos_abs (40, hor=-7.00000, ver=2.00000, dis=610.00000);
im_set_live (40);
im_winpar_write (40,x_pos=204,y_pos=171,x_size=176,y_size=256);
im_cont_process (40, REF_ELEM);
sen_do_measure (60);
sen_pos_abs (60, hor = 0.017453);
db_put_observ (2);
db_set_observ (2);
sen_pos_abs (41, hor=5.00000, ver=12.00000, dis=665.00000);
im_set_live (41);
im_winpar_write (41,x_pos=200,y_pos=150,x_size=164,y_size=256);
im_cont_process (41, REF_ELEM);
sen_do_measure (60);
im_cont_calc (ALL, REF_ELEM);
. . . . .
```

Fig. 5. Example of measuring program for a circle element measurement

6.4 Hardware Control

If the interpreter calls functions for image processing or sensor manipulation, these commands are sent to the controller module (see Fig. 4) and will be executed in the controller processes. During run-time the controller module consists of different concurrent processes which principally enable sensor control in parallel (time sharing). This means that it is possible to position a sensor (e.g. rotary table) concurrently to a second sensor (e.g. RSC) while other independent actions (e.g. database access) can be performed. Significant time saving during measurement process can be obtained. Each sensor group (cameras, table, lamps) are processed in a seperate UNIX process.

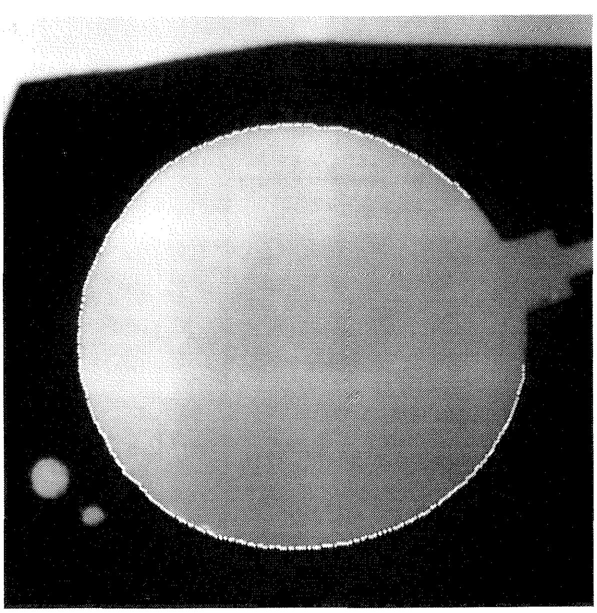
Using standardized UNIX and TCP/IP control mechanisms it is possible to install the complete software package either on one machine or, if necessary, implement the controller module on a second processor in order to increase computing power.

7. APPLICATIONS

Fig. 6 illustrates the measurement of a circular hole for a loud speaker in a dash board which is made of black plastic. In this case there are two RSC images without rotation of the turntable. In both images, a part of the hole contour is extracted. Since it is an incomplete circle, an open contour with user-defined start and end points is detected. Illumination is by direct spot lighting.

Fig. 7 shows an example of cylinder measurement applied to the inspection of a cooling tube made of black rubber. In this case either diffuse illumination or the intergrated light table could be used. Two images with different cameras and a rotation of 90° have been taken. In each case two edges of a cooling tube part have been extracted for determination of the cylinder in 3D space.

Fig. 8 presents the measurement of two straight lines at the edge of a car door made of grey sheet metal. A combination of diffuse and direct illumination has been used. A part of the greylevel contour of the edge has been extracted in each image. The corner point of this feature can be calculated as a line intersection in space. The line element algorithm is sometimes not able to detect non-identical object lines if only two images have been taken. In this case a minimum number of three images is recommended in order to avoid errors in line calculation.



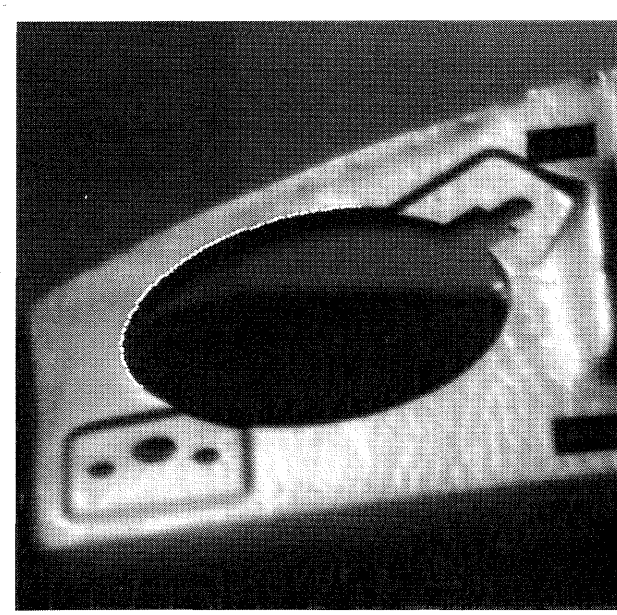


Fig. 6. Measurement of circular loudspeaker hole

left: Countour extracted from image of top RSC

right: Contour extracted from image of center RSC

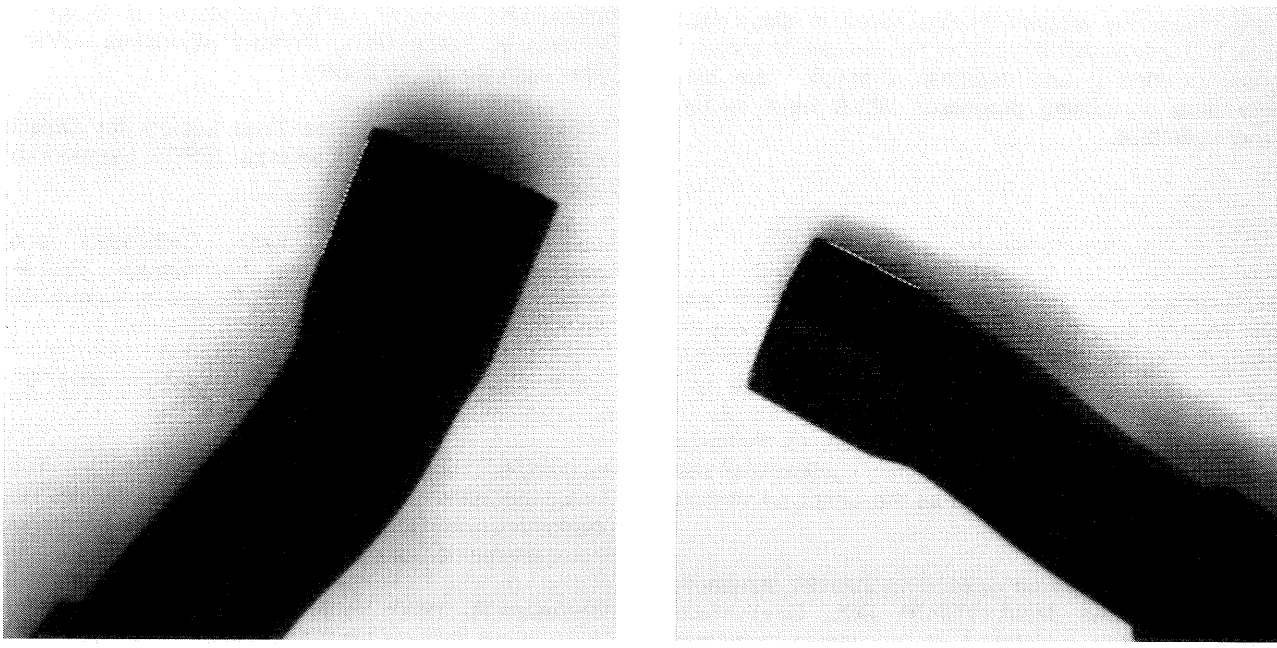


Fig. 7. Measurement of cylindrical cooling tube

left: Edge contour extracted from image of top RSC

right: Contour extracted from image of center RSC, 90 °

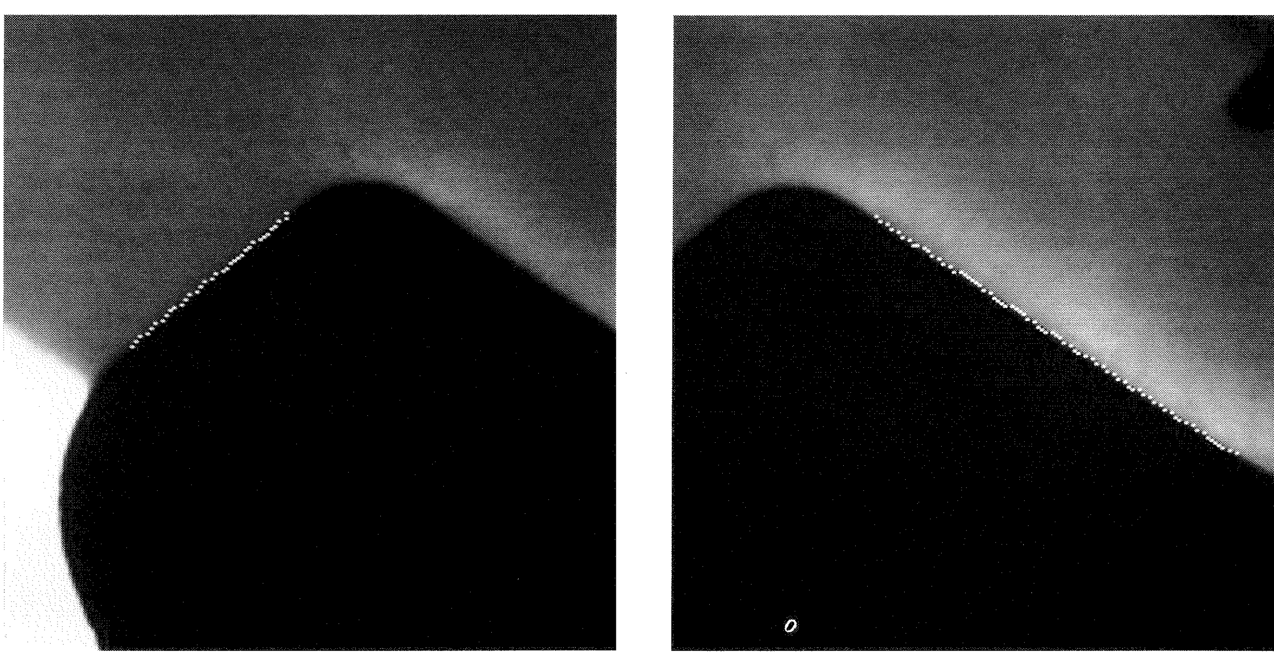


Fig. 8. Measurement of corner point on sheet metal car door

left: First contour extracted from image of RSC

right: Second contour extracted from image of RSC

The average measuring time for a 3D element with two images is currently about 30 seconds. In this case the whole measuring program is processed in sequential mode, that means that there is no parallel sensor control. Sensor positioning and database interaction are the major time consuming processes which have to be further optimized.

7. SUMMARY

The Programmable Optical 3D Measuring System (POM) was initially developed for an application in quality assurance in the automobile industry. It is not a single purpose machine but, due to its flexible hardware and software concept, it can be used for a large variety of applications. In this respect it is possible to configure lower cost solutions with simpler sensor configurations as well as high-end systems such as the prototype version for VW.

The concept is based on well-known industry standards (UNIX, X-Windows, Motif, TCP/IP, SQL, C++) which enable the easy adaptation to advancing computer technology in the future. Program interpreter and database are key modules within the whole software package.

On the one hand the economical benefit of the system can be achieved with the replacement of a number of expensive gauges. Additional costs due to modifications of objects during their lifetime are kept small because measuring programs or even sensor configurations may easily be changed.

On the other hand optical metrology is useful for those applications where an object can not be measured with physical contact methods (CMM) due complexity of form, surface characteristics or non-rigid materials.

POM is mainly designed for 3D data acquisition of points and elements. The post-processing of this data (e.g. connections of elements, analysis according to ISO standards etc) must be performed by specialized software packages (e.g. Leitz Quindos). Future developments will incorporate these functions in order to offer a complete solution for the customer's needs.

8. ACKNOWLEDGEMENTS

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