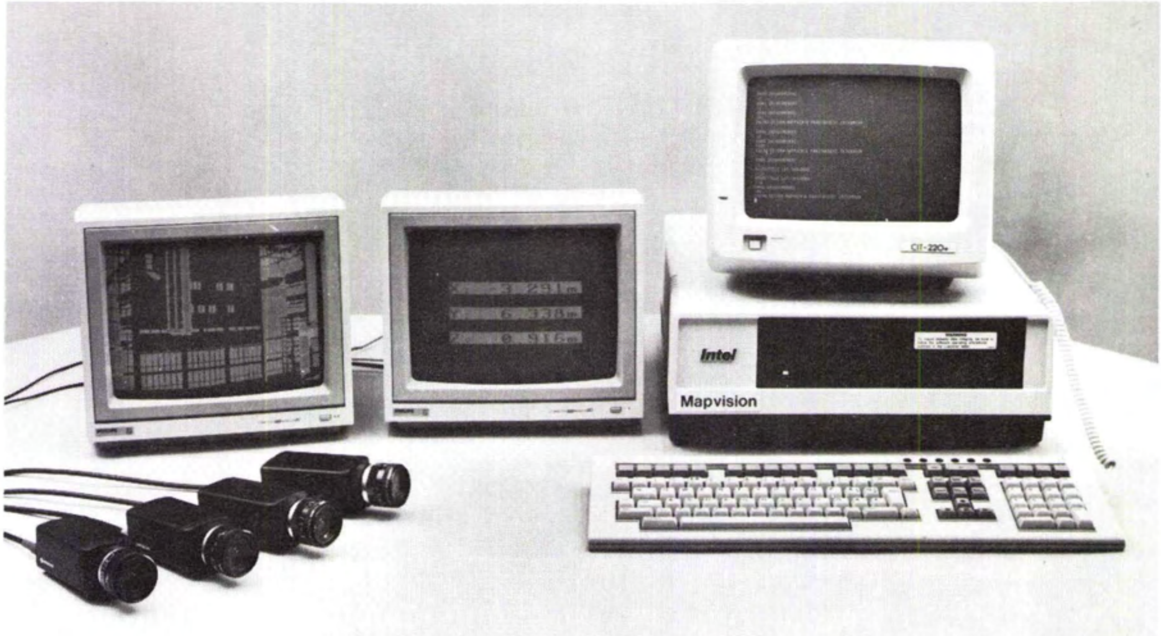

FRONTISPIECE. Mapvision (Haggrén, 1986a).

Mapvision: The Photogrammetric Machine Vision System

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ABSTRACT: Mapvision is a photogrammetric machine-vision system developed by the Technical Research Centre of Finland primarily for industrial inspection and quality control applications. The system consists of four simultaneously operating solid-state cameras and an especially programmed photogrammetric microprocessor. The three-dimensional measuring accuracy is better than 1:5,000. Mapvision is an automated system enabling the dimensional feed-back and interaction between computer-aided design and numerically controlled manufacturing phases.

INTRODUCTION

PHOTOGRAMMETRY AND MACHINE VISION Generally, photogrammetry is the art, science, and technology of obtaining reliable geometric information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images (Slama, 1980). Primarily the general means used for topographic mapping, photogrammetry has already proven its merit even in extreme machine vision applications (Steklasa, 1985). At present, real-time photogrammetry is becoming increasingly important in industrial machine vision (Real, 1986).

PHOTOGRAMMETRY FOR INDUSTRY

In non-topographic close-range photogrammetry, when using analog images and as applied today to industrial metrology, the objects to be measured are usually large structures like ship blocks or even halves of ships, aircraft assembly tools, or antenna dishes (Karara, 1985). The three-dimensional geometric information derived from these measurements is closely bound to the shape and size of the structure itself and its deviation from the design shape, as well as with the compatibility of the structures to be fitted to each other or with the deformations caused by external physical phenomena during the manufacturing processes.

PHOTOGRAMMETRY FOR MACHINE VISION

In recent years the rapid development of digital imaging and image processing techniques has resulted in close-range photogrammetric solutions being a part of the most effective machine vision systems. Real-time photogrammetry was first introduced in the early 70's, for example, by the National Research Council of Canada, and later reported by Pinkney (1978) and Kratky (1979). The onward rapid evolution of modern microelectronics has further improved the single-camera concepts of those times to more general and sophisticated ones, which take full advantage of photogrammetry in the use of several cameras operating simultaneously. The recent stage of the development of these multi-camera systems is outlined by El-Hakim (1986) and Grün *et al.* (1986).

MAPVISION

Mapvision is a photogrammetric machine vision system. It had its origins in a three-year research program on digital image

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processing at the Technical Research Centre of Finland (Haggrén, 1984). The prototype system was first internationally published during the SPIE Conference on "Optics in Engineering Measurements" in Cannes, France in 1985 (Haggrén, 1985). The novel version, which is already being used for quality control tasks, became operational in 1986 (Haggrén, 1986a; Leikas, 1986; Haggrén, 1986b). The first reference installations of measuring vision systems based on Mapvision technology were made in early 1987.

Design Criteria for Mapvision

Mapvision is systematically designed by taking into account the following primary criteria:

- The orientation of the image acquisition components, i.e., the cameras, should remain free in relation to the objects to be measured. The camera set-up is thus more adapted to the overall manufacturing and process specifications than to the measuring geometry.
- The system should be based mainly on commercially available off-the-shelf components. No manufacturing of high precision mechanical parts or other special components should be needed for the construction of real-time photogrammetric systems.
- The nominal accuracy and time specifications of the measuring system should be adjusted according to each individual application and should not be restricted by the basic measuring system itself.
- The measuring system should be easily adapted and equipped for manufacturing applications and should be maintained by operational personnel without any need of a thorough knowledge of photogrammetry.

REAL-TIME PHOTOGRAMMETRIC PROCESSING

Principal Idea

A real-time photogrammetric processor is a device which, by means of digital images, aims to identify and locate object details in three dimensions. Image processing should be performed during the recording of the imagery and without any further delay in relation to the main processes.

Mathematical Background

All the necessary geometric information for the three-dimensional determination of object details is primarily stored in the two-dimensional images. With at least two such overlapping images, the three space coordinates of object details are derived by triangulation. The mathematical formulation used for the coordinate transformations in close-range photogrammetry is basically the same as has been developed over the years for aerial mapping and triangulation (Slama, 1980; Wong, 1975). The approach presently used in Mapvision is the direct linear transformation. The advantage of this is that the solution is linear, i.e., no initial values or iterations are needed. This enables the direct transformation from image coordinates to object space coordinates and vice versa without any intermediate transformations through the calibrated camera coordinate systems (Karara *et al.*, 1974).

Space Resection

The actual transformation parameters for real-time photogrammetric systems are determined by a system calibration. After the set-up of the system, a set of control points with accurately known positions are first identified and located on images. The two-dimensional image coordinates are then used for the space resection of each image, independent of each other, and the transformation parameters are then solved without any *a priori* information regarding the cameras or their orientations (see Figure 1). Essentially, the mathematical model of the resection has to cope also with all systematic geometric distortions of the information flow during the projection.

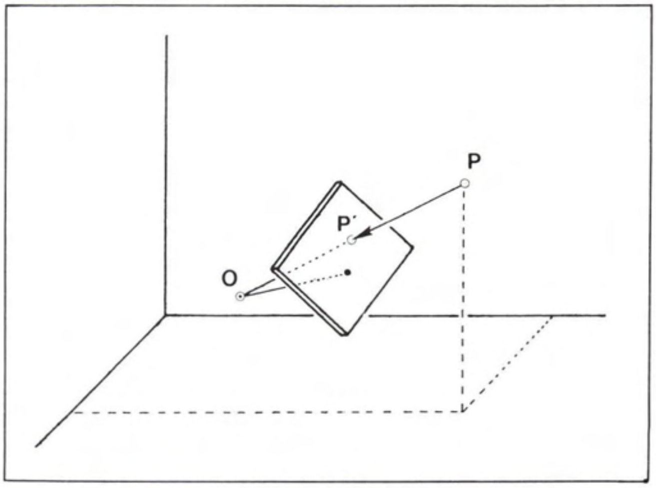

FIG. 1. The photogrammetric measuring has its origin in the geometric model, where the object point **P** is projected through the project center as an image point **P**′ (Haggrén, 1985).

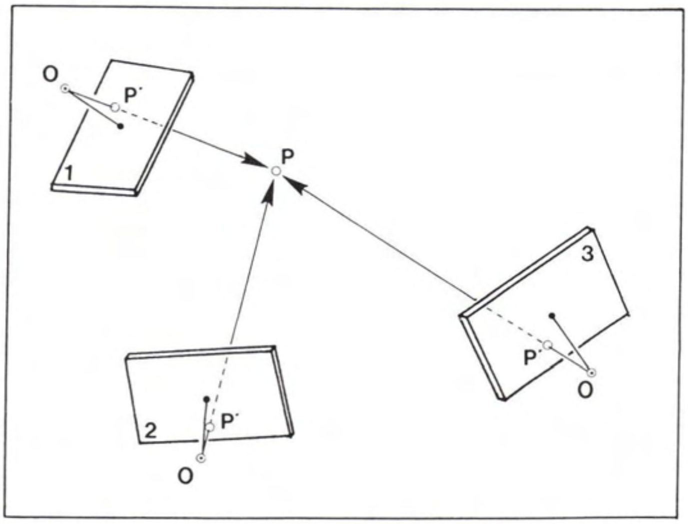

FIG. 2. The intersection of the object point is made by a reverse and simultaneous projection using reconstructed image space vectors **OP**′ (Haggrén, 1985).

Intersection

After the calibration of the system, every object space detail derived from images and viewed by at least two cameras at a time may be located. This is done by an intersection, which is a reverse and simultaneous transformation from the two-dimensional image coordinate observations to the three-dimensional object space coordinate system (see Figure 2). The transformation parameters are those determined during the system calibration.

Accuracy Potential

Photogrammetry as a measuring technique is well suited to high accuracy demands. The most recent examples when using analog images are to be found in industrial and engineering fields, where relative accuracy potentially as high as 1:250,000 for photogrammetric mensuration has been reported (Fraser *et al.*, 1986). The relative accuracy of real-time photogrammetric systems is mainly limited by image resolution. When applied to industrial measurements, the minimum accuracy demands are about 1:5,000, which means 1 mm in 5 metres. This requires a tenfold pixel interpolation of the image elements when using a digitizing rate of 512 by 512 pixels. The original goal for the

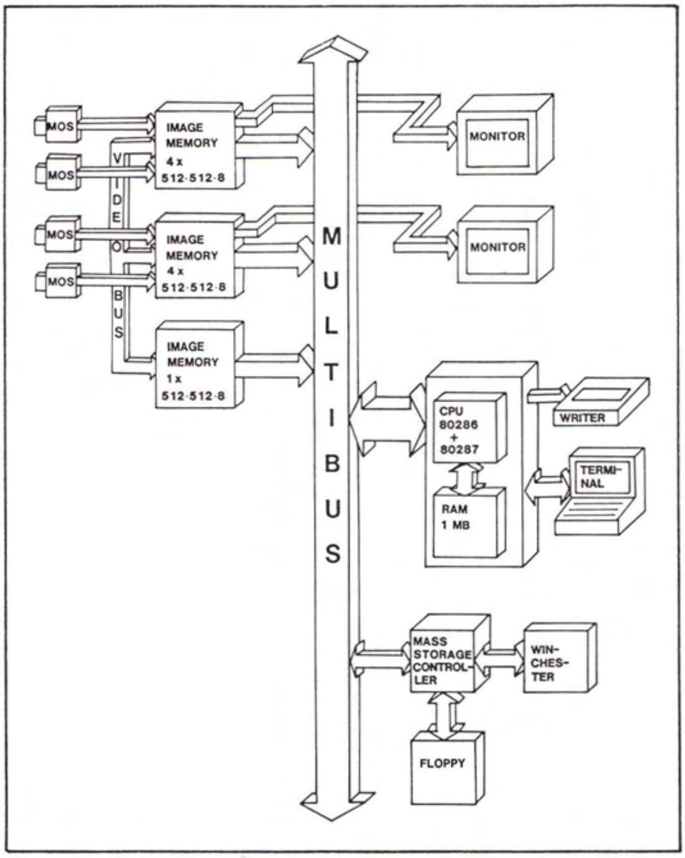

FIG. 3. The Mapvision system diagram (Haggrén, 1986a).

accuracy rate of the Mapvision was 1:5,000 and is presently about 1:10,000.

MAPVISION

RECENT STAGE

The first operative and stand-alone Mapvision system was built by the Technical Research Centre of Finland in 1986 (Frontispiece). This was constructed specifically for potential application development purposes. The first practical experiments using Mapvision have already shown that the system is versatile in fulfilling the original design criteria (see the Introduction).

SYSTEM DESIGN

Principal structure. Mapvision consists of two main parts: one for image acquisition and one for image processing. The system diagram for Mapvision is shown in Figure 3.

IMAGE ACQUISITION.

Fundamentally Mapvision is designed to make use of any kind of solid state video camera. In the Mapvision discussed here four Hitachi VK-M98E 50Hz black-and-white cameras are connected to the system. Each camera contains an MOS imager chip with an array of 577 by 388 image elements having respective vertical and horizontal orientation.

Timing. The cameras are synchronized with an external pulse generator and are operated simultaneously in two pairs. Within each pair the two cameras are mutually locked to each other so that the system also has the ability to measure details in moving objects. On the other hand, the camera pairs have a difference of 40 milliseconds in relation to their timing for frame grabbing. All the cameras are further synchronized to the image digitizers and the processor.

Image processing. Image processing is performed by an especially programmed photogrammetric microprocessor system. The modules of the processing system are

- The host computer (Intel SYS 310-17C)
  - — CPU: 8 Mhz 80286
  - — NDP: 8 Mhz 80287
  - — RAM: 1 MB
  - — winchester: 19 MB
  - — floppy: 320 kB
  - — operating system: RMX 286
  - — compilers: Fortran-286, PL/M-286, ASM286 (assembler)
  - — bus: Multibus I
- Video digitizers (Matrox)
  - — 1. MIP-1024M, 4 image memories of 512 × 512 × 8
    2. MIP-1024M, 4 image memories of 512 × 512 × 8
    3. MIP-512S, 1 image memory of 512 × 512 × 8
  - — processors: LUT-functions, hardware ALU for real-time execution of logical and arithmetical operations
- Software
  - — MAP for image processing and intersection
  - — MAPCAL for calibration/resection

OPERATION

Basic structure. The operation of Mapvision is arranged in two phases. The system is first set up and calibrated. Following this step, the system is operated for the measurement of three-dimensional coordinates (see Figure 4).

Calibration after the set-up. Before any measurements are made, the calibration routine has to be carried out. The system is calibrated by imaging 15 to 25 points, or for larger object space volumes by even more points, with known three-dimensional coordinates. These coordinates are most easily determined by theodolites at the time of calibration. Thereafter, the system solves for the transformation parameters to be used for the succeeding measuring phase. The transformation parameters include all camera orientations and necessary geometric lens distortions. The calibration phase, for example, for object space volumes with the principal dimension of about 5 metres usually takes less than one hour and is valid as long as the cameras are not moved in relation to each other.

Actual measuring. In the measuring phase, the details to be measured on the object or in the object space are first signalized with a laser beam or with specific targets. The laser beam is used for projecting discrete spots on the object surface in the case where the whole object geometry should be digitized. The targets are used for distinct object details. The signals are then identified and located in the imager arrays of each camera, and the three-dimensional coordinates are intersected from the image coordinates using the calibrated transformation parameters. The measuring time for one point is 1.5 seconds. If there are some preliminary data at hand for the image coordinates of the signals, the measuring time will be reduced. For example, the measuring of an averaged observation with ten repeated pointings takes only 3.6 seconds.

Signal extraction. The signals are identified in the images by subtracting the actual images from the so called reference images (see Figure 5). After subtraction, the signals are squared with a window of the size of 31 by 31 pixels. The noiseless background is thresholded and the center of gravity of the remaining signal areas is calculated by using all the original gray scale information.

Operation modes. There are presently four different modes in which to operate with Mapvision. The basic mode is mainly for research and demonstration purposes and the other three are for different kind of applications. The basic mode is also used for the interactive development of further potential application modes. It includes several operations for image management, real-time processing of input images, general image processing, measuring, output, and hardcopy.

The application modes are

- For pointwise measuring of signalized object details by using single or repeated observations. The performing time for one measurement is 2.7 seconds. When averaging with ten observations, the total

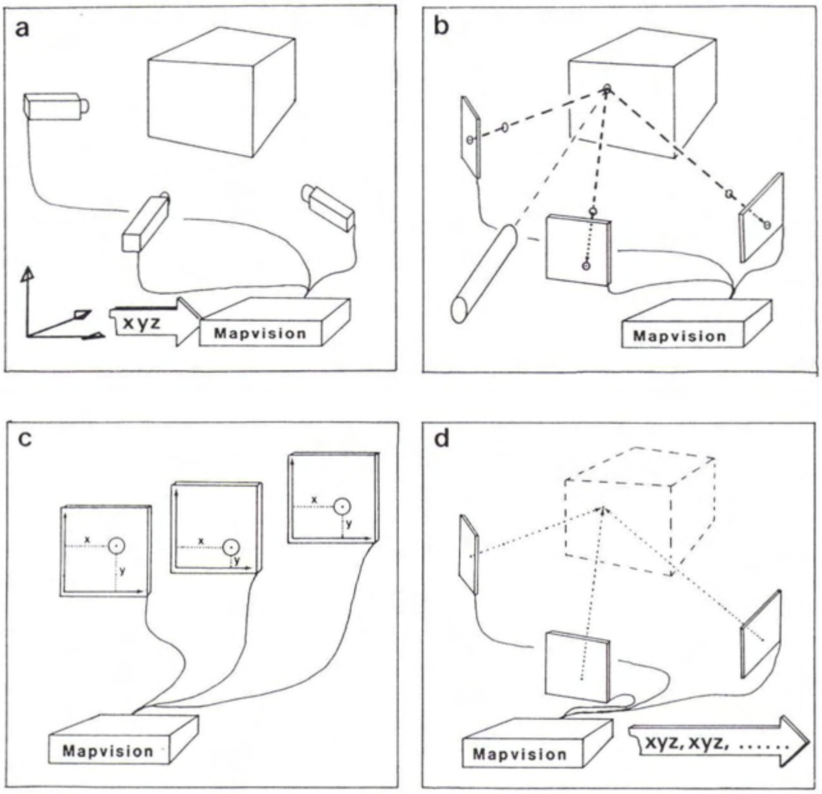

FIG. 4. The functions of the Mapvision system. (a) First, the system is set up, calibrated, and the transformation parameters from two- and three-dimensional coordinates are solved using *XYZ* control points. (b) In the surveying phase, the new points to be measured on the object space are projected onto the image planes. (c) Then the points are identified and located on the images, and (d) finally, the three-dimensional coordinates of the points are calculated using the calibrated transformation parameters (Haggrén, 1986a).

measuring time in this mode is 4.9 seconds. Also a 3 by 3 convolution may be used. Then the total time for one observation is 2.8 seconds.

- For pointwise measuring of object surfaces signalized by the laser beam, the performing time for one measurement is 1.5 seconds.
- For continuous digitization of object surfaces signalized by a scanning laser beam, the sample interval is 1.5 seconds.

The selection of application modes will be further modified with respect to new and operative applications.

SPECIFICATIONS

Accuracy. The recent interpolation rate of the Mapvision images coincides with a sub-pixel resolution of approximately 0.05 pixels, which is equivalent to a relative accuracy of 1:10,000. The three-dimensional repeatability of a single object space measurement, for example, when using the tenfold pointings, has been even better and is about 0.02 pixels. This resolution enhancement is explained by the high redundancy which results from using four cameras simultaneously for the intersection.

Operating ranges. The measuring ranges are generally not limited by the Mapvision itself but are mainly due to the camera specifications and overall working conditions. So far the operating ranges when using the Mapvision for different kinds of applications have varied between 1 to 25 metres. In the case of larger object space volumes, the total scene coverage of the four images may be enlarged either by using wider-angle optics or by using a kind of bridging technique. In the latter case, the camera set-up is organized so that each object detail to be measured is covered by only two images at once. This allows the image scales to be kept as large as possible and the measuring accuracies to be higher.

APPLICATIONS

GENERAL

As a three-dimensional measuring domain, real-time photogrammetry lies between coordinate measuring machines and digital theodolite systems. Generally, Mapvision is a non-contact and optical measuring device having a high automation potential in closing the bi-directional information loop between "as-designed" and "as-built" data bases of modern computer-integrated manufacturing systems. There are now two introductory applications where Mapvision is used for automated inspection and measurement, namely dimensional control and quality assurance.

DIMENSIONAL CONTROL

The preliminary application within dimensional control is the quick check of symmetry deformations of airplanes (see Figure 6). The rigging checks are carried out by measuring symmetry distances between diagonal check points of the body structure. The comparison measurements will be individually repeated at regular intervals or occasionally after heavy landings.

QUALITY ASSURANCE

Within quality assurance applications, the first experiments have been done for ship building and manufacturing processes. The aim is to develop a semi-automatic on-site inspection system for verification of curved ship body elements (see Figure 7). For quality control purposes the Mapvision will be further connected to computer integrated manufacturing systems especially to their specific modules of analysis of measuring data.

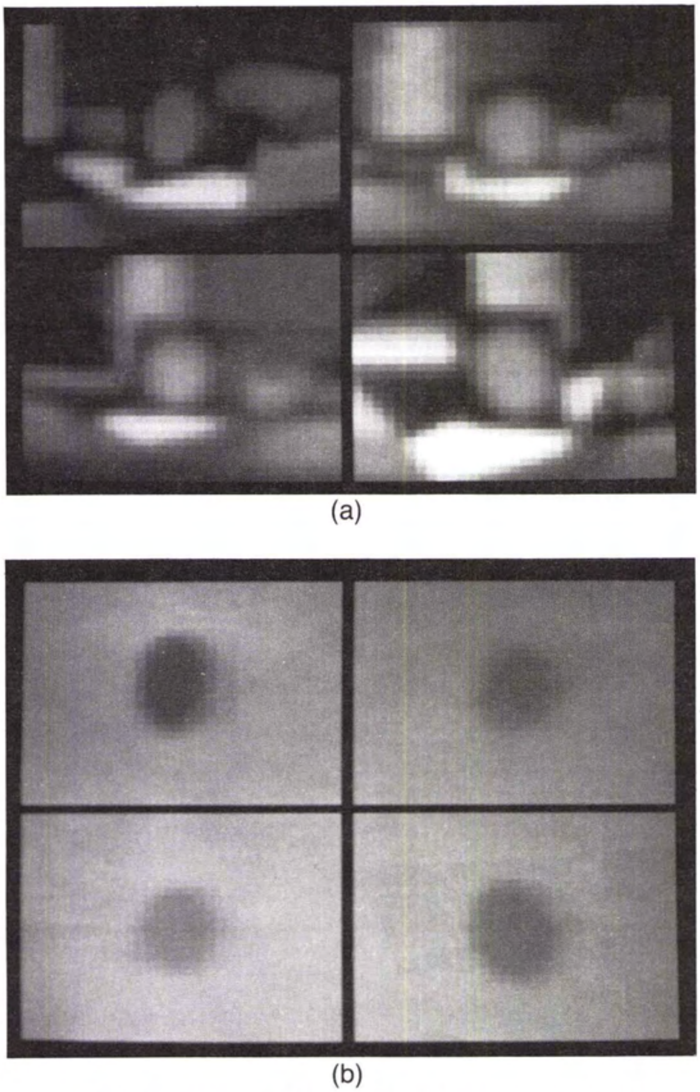

FIG. 5. The signal extraction in the case of reflective targets. (a) The reference images of the four cameras, each including the target without external lighting. (b) The same scenes after the lighting of the target and subtraction. The windows are 31 by 31 pixels in size.

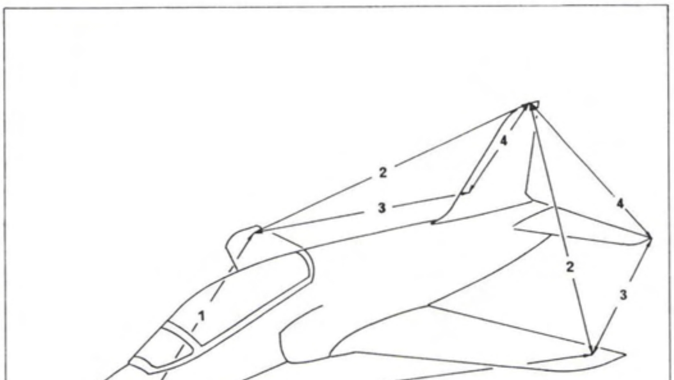

FIG. 6. The symmetry check distances for an aircraft body.

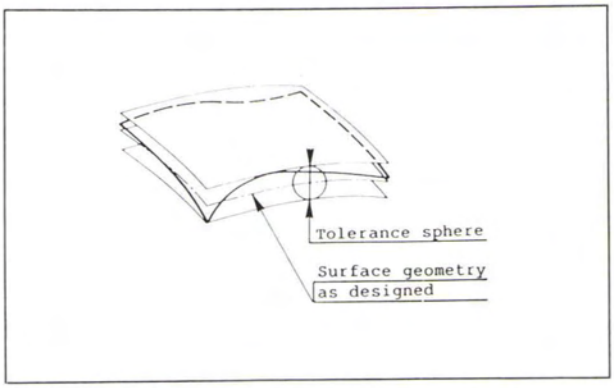

FIG. 7. The three-dimensional quality control of curved surfaces.

APPLICATION OUTLOOK

Mapvision has already proved to be suitable for some distinct and actual practical applications. In developing Mapvision, we have taken into account that the system can be further used for new applications with new requirements. The whole variety of traditional machine vision applications including gauging, flaw detection, robot quidance, assembly control, surveillance, etc., is now becoming three-dimensional. Because of the use of video cameras, the potential applications relate more to the image acquisition systems than to Mapvision itself, so that applications like high-speed or underwater photogrammetry are also within relatively close reach.

CONCLUSIONS

The development of real-time photogrammetric systems at the Technical Research Centre of Finland has now reached the first maturity stage. There are no technical obstacles today in applying photogrammetry to metric machine vision. The accuracy limit of 1:10,000, real time measurements in about one second, and the applications for automated inspection and measurement handled in this paper are to be considered only as practical mileposts on the way. The real challenges lie far beyond, and are affected constantly by the rapid development of electronic or electro-optical components, and processing technology.

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