REAL-TIME PHOTOGRAMMETRIC SYSTEMS
- WHO ARE THE DEVELOPERS ?

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ABSTRACT

Industrial measuring systems are developed in a large number of scientific and technical environments. In photogrammetry, certain knowledge and traditions influence the development in a direction where precision, reliability and 3D are terms of great importance. Other developers may have different background in their work, leading to other solutions. A study concerning these differences is made, illustrated by systems developed by photogrammetrists and similar systems from the non-photogrammetrical 'outer world'. Several aspects are investigated, e.g. data collection, complexity of measurements, methodology, degree of automation and implementations. The main question and the motivation for this paper may however be formulated in a less technical, but more implicit way: Real time photogrammetry - are the traces of a photogrammetric tradition still visible?

1. BACKGROUND AND INTRODUCTION

The intention of this paper is not to give an overall view of the development in real-time photogrammetry or to present the latest and fastest hardware, but an attempt to try to find the traces and fingerprints of the photogrammetrists who are involved in the development of real-time measuring systems. Four systems are chosen to illustrate this intention, two primarily developed in the photogrammetric society and two primarily developed by people from other scientific areas. The systems are all commercially available. In this study, only passive image acquisition systems are discussed. This means that 3D systems like laser range finders and laser interferometry systems are excluded, even though they could fit into the same context.

The paper is divided in three main parts. The first part is discussing some criteria for a system being 'photogrammetrical' and how these criteria are dealt with and looked upon from different view-points. The second part is looking at the basic components of a vision system for photogrammetrical close-range applications with a discussion based on the solutions used in the four illustrating systems. The third part is a short description of the four systems. The paper is closed with a final discussion.

The two systems which are developed mainly by nonphotogrammetrists are illustrated through the diagrams by circles, ○, ●, and the two systems developed mainly by photogrammetrists are represented with by, □, ■. All of the system are developed in Scandinavia. The systems are not compared looking only at their performance abilities for various operations and applications, but also how and why certain solutions and methods were selected. Key words in the photogrammetric society like precision and reliability are looked at with special interest to see if there are differences in the way they are treated.

System #1 ○

MNS, Metronor AS
A general 3D system using two high resolution cameras. Measures on a projected laser point. Applications in various industrial fields like CAD-modelling and QC.

System #2 ●

MacReflex, Qualisys AB
A general motion analysis system using 1 - 7 cameras, each with a dedicated hard-ware unit. Measures on
reflective targets. Most applications in bio-medicine.

System #3 □

Mapvision, Oy Mapvision ltd
A general 3D system using 2 - 22 cameras. Measures on both defined natural points and target points. Mainly constructed for industrial applications like positioning and deformation.

System #4 ■

Track-Eye, Innovativ Vision AB
A high speed 3D motion analysis system using 2-6 analogue/video film cameras. Measures and tracks target points in digitized images.

The numbering of the systems has no qualitative meaning.

2. DEFINITIONS

The terminology in real-time photogrammetry is rather confused and even if attempts have been made toward a common grammar, some of the terms are defined in the context of this article to avoid misunderstandings.

Real-time, time constrained and *video-rate* are terms which are related and partly overlapping each other. By *video-rate* is here meant a standard video imaging system, generating images at 25/50 Hz. Many systems uses its own image acquisition speed, which here are related as being either higher or lower than the standard video-rate. *Real-time* in machine and robot vision are often implicitly meant to be the standard video-rate. A more general definition of real-time is *time-constrained*, giving a limited time in which the task must be solved. In this paper real-time systems are equivalent to time constrained systems.

By *Calibration* is, in the photogrammetric society, mostly meant the determination of the inner orientation of a camera. In machine vision the term often stands for the determination of the outer orientation parameters as well. In this paper *System Calibration* is referred to as the determination of the absolute orientation *and* the inner orientation if they is determined simultaneously. If the inner orientation is determined separately, this is referred to as *Camera Calibration*. The term *system calibration* is chosen in favour of outer orientation or absolute orientation since it is more relevant when talking about an industrial installation.

3. A PHOTOGRAMMETRIC SYSTEM

As the title of this article indicates, the primal interest is in the developing process of the close-range systems, not so much the actual performance of the systems themselves. To be regarded as photogrammetric, a close-range system must however meet certain criteria. One suggestion for these criteria are given by (Grün, 1991):

- **Potential for high precision and reliability (redundant sensor data)**
- **Capability of self-diagnosis (quality report)**
- **Task flexibility with respect to 3-D object reconstruction functions**

This 'definition' of a photogrammetric system may be valid within our own society, while in computer vision the term 'photogrammetry' usually stands for the various orientation procedures of stereo images which here is related only to the third criterion. The definition implies of course that a system developed by a photogrammetrist may be said to be non-photogrammetric, while a system developed by a machine vision engineer may be seen as photogrammetric in our eyes.

When designing a real-time measuring system, all three criteria will by their nature be in conflict with the time constraints, since the time complexity of the computations are high for each of them.

3.1 High Precision and Reliability

High precision is possible to achieve with the methods available in data extraction and data analysis (e.g. Haggren, 1990). Several systems aiming at high precision reach results which are as good, or better, than a human operator in cases where the targets are well defined.

The reliability is a more delicate matter since it touches the part of a system which is harder to describe in statistical figures: its insensitivity, or robustness, against erroneous data or model outliers. In a manually operated system, gross errors are rare and fairly simple methods can be used to locate them. When a process is automated or semi-automated, as in the case of real-time measuring systems, the need for more robust methods becomes more obvious. The robustness should be incorporated in all the parts of the measuring process, to ensure that single or groups of erroneous data do not influence the final output.

Two aspects of robustness are of major concern (Förstner, 1987):

- Robustness of design
- Robustness of estimation

The robustness of design is concerned with the ability to test the models with respect to model errors and with the sensitivity of the result to errors. The Least Squares, LS, techniques together with statistical analysis are the main tools.

Robustness of estimation is concerned with optimization procedures which eliminates or reduces the effect of model errors. Other types of estimators which are more robust against model errors than the LS have been developed, e.g. Least Median Squares (Rousseeuw, 1987) and Minimum Description Length (Axelsson, 1992). These estimators, which can handle up to 50% of erroneous data, all lack an analytical solution. Instead, a systematic or random search must be used for finding the solution. This makes the methods computationally very complex. If the number of parameters are very high, as e.g. in a bundle adjustment these methods are not suitable. For other applications, like e.g. relative orientation or orientation of a single camera, the methods should be considered.

Comments None of the illustrating systems uses the second type, robustness of estimation. These methods are fairly new and the knowledge of them limited outside the statistical research environments. We believe that these method will play an important role in future systems, both in the extraction of image features and in orientation procedures.

The general view on the precision concept and if there are differences depending on the background was formulated by an electrical engineer as "...photogrammetrists think of precision in the cameras, images and all the different steps. We only relate to the deviations from a known reference object...". From the 'photogrammetric' side one person said that "...redundant observations are not fully utilized in non-photogrammetrical systems...".

When looking at the systems these comments seem to fit quite well. The systems developed by photogrametrists are more general in dealing with the redundant information from over-determined systems, even though the other systems may use the redundant information in some steps. The parts which are of special interest for redundant information is the system calibration and the point determination (data analysis).

3.2 Self-Diagnosis and Quality Report

A system operating over a time period must be able to control the quality of the output and to do the proper corrections during operation if necessary. A simple way of detecting errors in the output is e.g. to measure control points which are compared with their nominal values. If the detected error(s) is to be corrected, enough information must be provided by the system to locate, eliminate and update the error source.

To be able to do a statistical error propagation through the whole process, from image acquisition to data analysis, the different parts must be encompassed in a statistical framework, where results from one level can be be used in the next. The error theory developed for photogrammetry is well suited for this task since it already covers the image acquisition part and the adjustment part of the data analysis. Two parts in the process are however less investigated:

- data extraction

- robust adjustment methods

The *data extraction* methods used in image processing, e.g. edge and point detectors, are very seldomly producing statistical values of their performance. Methods used in a photogrammetric system should be able to produce this type of values to enable a correct statistical treatment of data, e.g. the Förstner interest operator (Förstner, 1987). A statistical propagation is also needed if a theoretical prediction of the results are to be done before implementation and installation.

To make the process less sensitive to gross errors, the adjustment of redundant data may be treated with more *robust methods* than the normal equally weighted LS. The statistical properties of such methods are not always known or possible to directly put in to the normal statistical procedures.

Comments The self-diagnostic capabilities of the systems are of very different nature depending of the degree of automization and application. Those of the systems which are manually supported rely mainly on the operator to detect errors. The more automated systems have the ability of detecting errors and in some cases to correct them.

Two of systems developed by photogrammetrists uses control points to detect any changes in the system orientation and will automatically update the orientation parameters if needed. They also use several cameras to get an internal control of the point determination.

The two systems not developed by photogrammetrists have other ways of detecting errors in the system calibration, e.g. known distances, but are not able to correct it without operator assistance.

As mentioned in 3.1 the different view on how to describe the precision for the systems is valid also for the self-diagnostics and quality reports. The error theory which is used in the traditional photogrammetric systems require a statistical model for all the different steps to enable an error propagation. The other approach is to empirically estimate the accuracy of the system and use these values without the statistical background. This is a fast and computationally easy method and also easy to understand for the non-specialists who are to use the systems.

3.3 Task Flexibility

The third criterion implies that photogrammetric systems are fairly general systems with respect to 3D object reconstruction. It may be argued that dedicated systems and even single camera systems with 2D capabilities might in some cases should be regarded as photogrammetric as well, as long as the extracted information from the images is metric.

Comments The generality of the 3D calcualations are partly depending on the type of measurments the system is able to do. Grey-level based data extraction, used by the two systems developed by photogrammetrists, is in principle more general than target measurements, but many other factors, like sampling speed and data analysis, should also be considered.

4. REAL-TIME SYSTEMS - THE SYSTEM PARTS

Even though photogrammetric systems may differ between each other in many respects, they are usually having the same basic components (fig 1).

Different tasks will certainly put different restrictions on the time constraints for the systems. Some applications have the hardest constraints on the image acquisition part, e.g. high speed motion analysis systems, where the extractions and analysis of data may not be completed or even started between the acquisition of two image frames. Other, more quality control or robot oriented tasks, may need to perform all steps in sequence in order to be able to make a decision in the time constrained cycle.

In the following section the different parts of the photogrammetric system are discussed and the four systems are briefly described in this context.

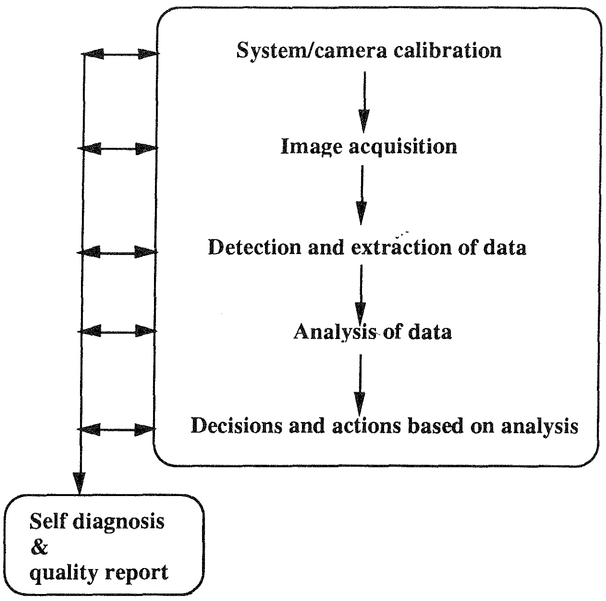

fig 1 Basic system design

4.1 System/Camera Calibration

The calibration of the cameras and systems are vital parts for the system performance. They may be done simultaneously in a combined adjustment of the camera and system calibration parameters or as separated procedures.

4.1.1 Camera calibration The calibration of electronical cameras have been thoroughly investigated (e.g. Bösemann, 1990). The calibration must not only take into account the optical system of the camera but also the electronic parts. The traditional photogrammetric optical calibration adjust data to a mathematical model based on physical assumptions. This leads to e.g. the familiar polynomial equations for the radial distortion.

Another approach is to calculate the deviations, or errors, for each pixel. From the deviations a look-up table is created. This method is not concerned with the physical background of the errors. It is fast and easy to implement and especially suited together with the Direct Linear Transformation, DLT. The two systems which are not developed by photogrammetrists are using this approach (fig 2).

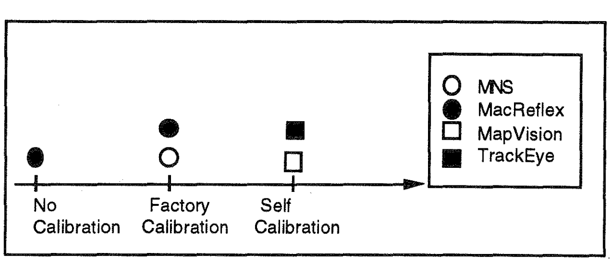

fig 2 Camera Calibration

4.1.2 System calibration The system calibration, or the outer orientation, is computed using either the DLT or the bundle adjustment (fig 3). The advantages of the DLT is, at least initially, its easy implementation and the simplicity of the outer orientation. The advantages of the bundle adjustment is its flexibility in the control, e.g. 1-3D points, distances, plumb lines, and its theoretical superiority and error propagation capabilities compared to the DLT. For a more comprehensive study of the differences between the DLT and the bundle approach see (Edgardh, 1992).

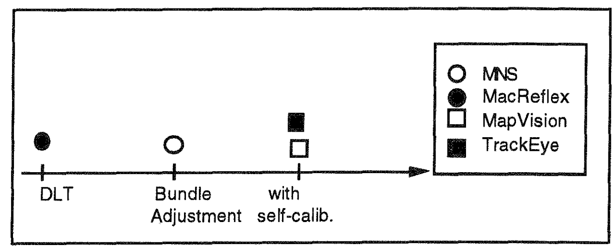

fig 3 System Calibration

Comments The camera and system calibration is a part in the measuring process where the differences between photogrammetrists and other engineers are visible.

In the camera calibration both of the systems which are not developed by photogrammetrists are using a factory calibration. This is motivated by the stability of the CCD cameras. Both the system measure on laser spots or on reflective targets which partly reduces the need of re-focusing the cameras or changing the aperture, an argument often brought against factory calibrations. It may however not only be a question of precision but also of reliability as one of the photogrammetrists expressed "...never rely on a previous calibration. The system should be calibrated after the installation and it must be fairly easy to re-calibrate both the interior and exterior orientation...".

The choice between DLT or bundle adjustment can be difficult in some applications. An advantage using the bundle adjustment together with CCD cameras compared to analogue cameras is the possibility of making several measurements after each other. Two systems, #2 ● and #3 □, utilize this technique to calibrate the systems. A known distance is moved around in the measuring volume until a satisfactory number of observations are made. This is also used for the self-calibration of one of the systems, #3 □. This greatly reduces the problem of calibration of both the cameras and the system compared to the traditional test field calibration.

4.2 Image acquisition

In close range applications, the typical image acquisition part consists of standard video-rate CCD-cameras. A good reason keeping to this standard is the large number of fairly cheap electronic components, ranging from the CCD-cameras over frame grabbers to hard ware implementations of basic image processing functions.

In the industrial environment, the production frequencies are sometimes deviating from the standard video rate in such a way that solutions with other image acquisition rates must be employed. Certain high resolution, non-standard CCD-cameras also have slower image generating cycle due to the read-out time of image data.

For the registration of very fast processes, with more than 500 frames/second, analogue high speed film cameras are still used to a large extent, even if CCD cameras with fairly good resolution are becoming available also for these purposes (fig 4).

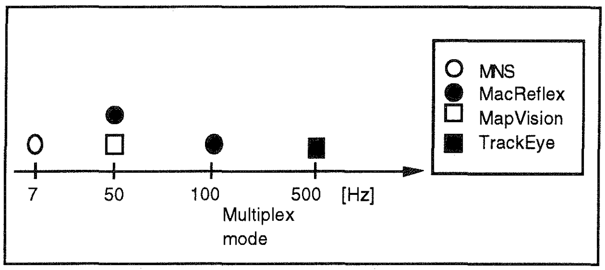

fig 4 Image Acquisition Speed

4.3 Detection and Extraction of Data

The extraction, or measurements, of data can be seen as an information compression and information extraction of the parts in the image which are of interest. This is primarily done by low-level image processing techniques. Two main types of information can be defined (fig 5):

- Area based information

- Point based information
    - Grey-level correlation techniques
    - Thresholding/slicing techniques

Examples of the first category are histogram or textures of defined regions. None of the illustrating systems use this type of information.

The point based information are mostly derived from an area in the image as well, but the purpose is to compute point coordinates. If the target points have different reflectance or emittance properties than the background image, a thresholding may be done to extract the target areas. This is a simple and fast technique. The measuring point can be defined by

Reflective markers
Projected laser spot
Light Emitting Diodes, LED's

Both the systems developed by non-photogrammetrists use this type of targets as their only data source, #1 ○ and #2 ●. System #3 □ uses it primarily for the system calibration.

The detection and extraction of the target points are fast with the thresholding technique, but it does not enable the system to measure on natural object points, e.g. corners. To be able to do so, grey level correlation techniques must be used. This is a time consuming task, but can be speeded up if the location of the searched pattern is approximately known, as is the case e.g. when tracking points in a motion sequence. This method is used by #3 □ and #4 ■.

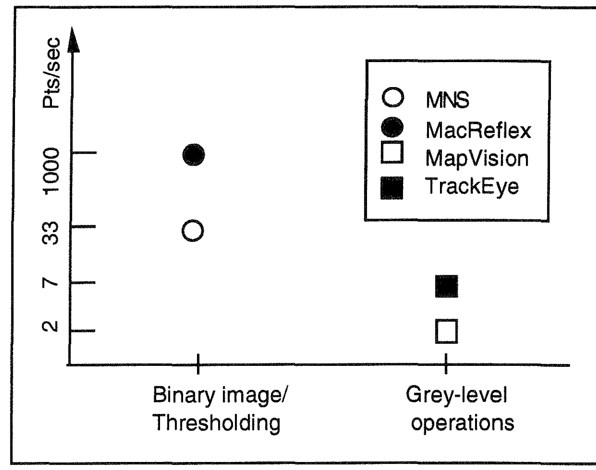

fig 5 Data Extraction

The precision of the extracted image coordinates are of course of vital interest for the final result. All of the illustrating systems claim a high precision in the measurements of the image coordinates, which means a 1/20:th - 1/50:th of a pixel.

If more complex image operations are to be done in real or near real-time, the implementations must be done in hardware. If the full frame must be processed even todays hard-ware implementations might not be enough. The amount of data in a stereo CCD system requires app. 12.5 Mb/sec (Grün, 1991).

Comments From an error theoretical point of view the data extraction methods used is mostly unsatisfactory. Very few, if any, of the systems can produce error estimates for the image coordinates which can be used in the further processing of error estimation.

The extreme difference in speed for system #2 ● is due to the fact that each camera has a dedicated hardware unit capable of measuring 20 pts/50 Hz image. There is no further analysis of data in real-time as for the other systems.

The ability of measuring on natural targets requires grey-level based methods. This reduces the speed of the point measurements, but if more complex operations are to be developed in the future they must anyway be done in the grey-level image. This would indicate that grey-level based methods are more in principle more general.

4.4 Analysis of data

Depending on the task, the analysis of data may range from the computation of single 3D coordinates or histogram analysis to the advanced reconstruction of complex structures and objects. In cases where the analysis is not a guiding part of an on-line process or too complex to be performed in the same cycle as the image acquisition and data extraction, the analysis of data is done as a separate phase. In cases where the final analysis require the whole set of measured data, e.q. generation of a DEM, this is done outside the time constrained image generating time cycle.

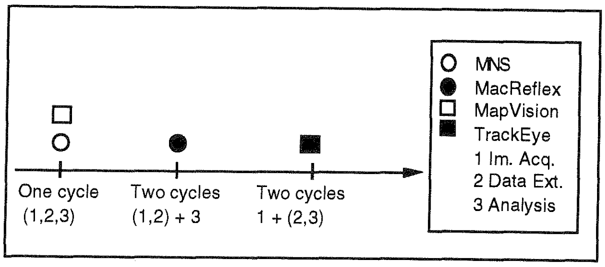

fig 7 Analysis Cycles

All analysis in one real-time cycle

MNS, e.g. Quality Control
Mapvision, e.g positioning

Image acquisition and data extraction in real-time and analysis in separate step

MacReflex, manual point identification and automated tracking

Image acquisition in real-time and data extraction and analysis in separate step

Track-Eye, image digitization, manual point identification and automated tracking

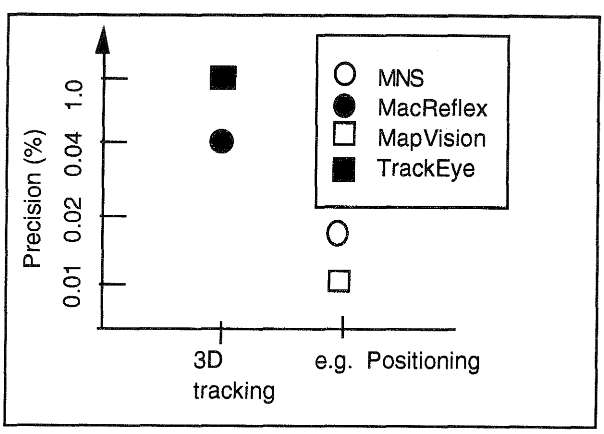

fig 8 Data Analysis, type and precision

Comments The precision of the systems are approximate and depends of course on the type of target point etc. The high speed motion system, #4 ■. has a different magnitude of precision depending on the different conditions for this application.

4.5 Decisions and actions based on analysis

If the task of the system is to guide e.g. a production line, the analysis of data should result in a decision based on a set of pre-defined rules. The decisions made by the system is mainly guiding the actions for the actual image at hand, but may also guide the future handling of images.

In the case of a separate analysis phase, the decisions made can only affect the processing of the images. The image acquisition and formation step can only be affected if the whole task is repeated.

Decisions in one cycle

Mapvision, e.g. moving an object in the assembly line

MNS, e.g. Quality Control

5. FOUR IDEAS - FOUR SOLUTIONS - FOUR SYSTEMS

The four systems which are used in the paper to illustrate the thoughts are here described in more detail. First the ideas behind and questions of special interest to this paper and secondly a small technical part. The following headlines are used for the description:

a Did you set up any clear goal before starting the development, or is the 3D system a continuation of earlier systems, e.g. 2D measurements ?

b Do all developing engineers have a similar background or do they come from different fields?

c How much do you think the scientific background has influenced the system design, and if so, which part could have looked different?

d How would you describe the 'photo grammetric thinking', if there are any, in the data extraction part calibration, orientation and 3D calculations

e How would you describe the system regarding
Precision
Reliability, robustness
Self-diagnosis

5.1 System 1 MNS, Metronor AS ○

a Continuation of earlier 2D system

b No photogrammetrists from the beginning. Background in electrical engineering with special competence in CCD arrays.

c Influences the thinking of how to handle precision. The calibration procedures might have looked different.

d Nothing special in the data extraction part. The bundle adjustment using known distances in the system calibration and the 3D calculations.

e The high precision of the system is made possible because of the high resolution cameras and the distinct targets. The precision is verified against a known reference, while the error theory is of minor interest. The reliability is in one sense limited since only two cameras are used. The special light pen works as an indicator if something is wrong with measurements or c ameras. There are no ways of automatically correcting errors during the measuring phase.

Technical Description

Two Videk Megaplus CCD-cameras (7 frames/sec)

System orientation with known distances

Measures on laser spots or LED's

33 points/sec

The measuring uncertainty is described as 0.05 + L/10000 (mm)

VME motorola 68030 for image processing tasks. HP workstation in Unix environment for operator

Special details:

Light pen for inaccessable points
Connections to various CAD-systems

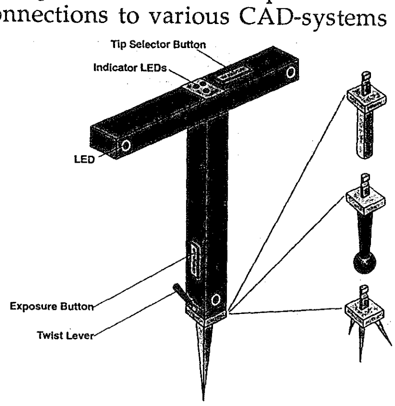

Fig 9 Light Pen

5.2 System 2 MacReflex, Qualisys AB●

a A new system with three goals

- Simple to use
- High technical performance
- Reasonable price

b Background in electrical engineering

c Did not know, but emphasized the need of competence in industrial development and manufacturing

d Nothing special in the data extraction part. Uses a DLT solution for the orientations, which they became familiar with during earlier work with the SELSPOT system.

e The high internal precision of the system is made possible because of the distinct targets and a special hardware unit for each camera. This also enables the very high sampling frequency, 20 points/50 Hz frame with up to 7 cameras. The external precision and reliability is partly due to the simple orientation procedure with a DLT using five points and one point for control. There are no automatic self-diagnostic in the system.

Technical Description

2 - 7 CCD cameras with dedicated hard-ware

System orientation with calibration frame, DLT

Measures on reflective targets

20 points/frame at 50 Hz, The different cameras may be connected in muktiplex mode to raise the image acquisition rate.

The absolute accuracy 0.04 %

Developed for the Macintosh environment

Special details:

Easy to use for operator
Very fast measurements of image coordinates

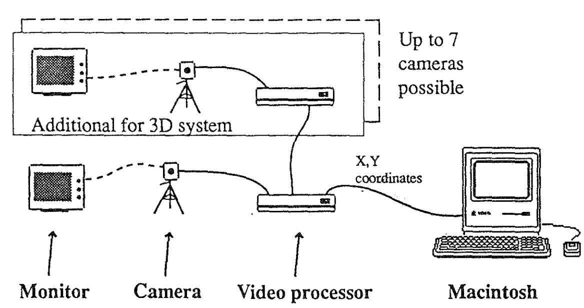

Fig 10 MacReflex System Configuration

5.4 System 3 Mapvision, Oy Mapvision ltd□

a Defined goals in 1977 which now are fulfilled

b Mixed background of surveyors and electronical engineers.

c The design of the system would have looked different if only one of the groups had been present, e.g. the calibration procedures.

d Utilizes the full information of the grey-level image to achieve high precision and measures one point at the time, which reduces the correspondence problem. The calibration is done as a bundle adjustment with self-calibration using known distances. This makes it easy to have a high number of points in the calibration phase.

e The precision is easily controlled with repeated measurements. To make this test relevant it should span over a longer time span e.g. two hours. The reliability is achieved by a high number of calibration points. The error tests are only looking at the residuals. The self diagnosis are of two kinds, internal and external. The internal diagnosis uses the fact that more than two cameras are used for the intersection of points. The external diagnosis is using control points and looking at the residuals.

Technical Description

2 -22 CCD cameras

System orientation with known distances, self-calibration of system after installation

Grey level based point measuring

0.4 points/sec

The absolute accuracy 0.01 - 0.02 %

Special details:

Self-calibration using distances
Very high accuracy
Can handle many cameras
Automatic corrections and self-diagnosis

5.4 System 4 Track-Eye, Innovativ Vision AB

a Continuation of earlier 2D system

b No photogrammetrists in the development of the main 2D motion analysis system. For the 3D analysis module photogrammetric competence were used.

c The influence of the design of the 3D module. The way errors are treated and their effect.

d Nothing special in the data extraction part. The bundle adjustment with self-calibration of the unstable part of the interior camera parameters.

e The high resolution scanner, 6.2 μm, together with a grey-level based tracking algorithm ensures high precision in the image coordinates. The reliability is mainly dependent on the number of cameras. The self-diagnosis is fairly well developed with residual control of known points which automatically starts a new system calibration.

Technical Description

2 -6 analogue high speed film cameras

System orientation with 3D calibration frame, self-calibration of un-stable parameters during motion sequence.

Grey level based point measuring/tracking

7 points/sec

The absolute accuracy 10 mm

Special details:

Self-calibration connected to self-diagnosis

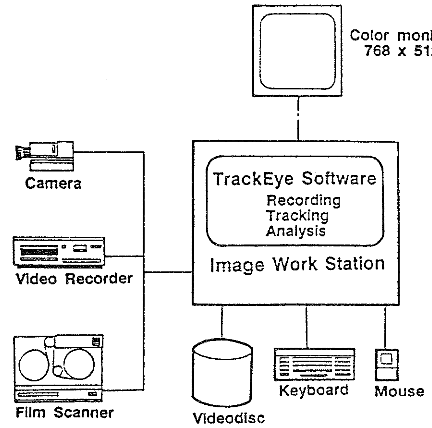

fig.11 System Configuration of TrackEye

6. CONCLUSIONS AND REFLECTIONS

The main intention of this paper was to recognize any differences between photogrammetric real-time systems depending on the background of the developers. The main characteristics of a real-time system can basically be described as:

Fast and Robust

The traditional photogrammetric approach, which crudely may be described as putting everything into large linearized LS problem, may be fine for aerial mapping, but the geometrical conditions and time constraints in industrial and other close-range applications are not always fitted for this. It may be described as robust but is not always as fast as wanted.

The machine vision approach which, very generally, may be said to be more attracted by direct solutions, is on the other hand fast but not as robust as a correctly treaten over-determined system.

There seem to be a contradiction between these two approaches, but it is also possible that a merging of the two ideas can be fruitfull. Direct solutions for fast estimations of e.g. initial values is engaging many researchers which e.g. resulted in the workshop at this Congress ,"Calibration and Orientation of Cameras in Computer Vision". Similar ideas were expressed at the "Second International Workshop on Robust Computer Vision" organized by prof. W. Förstner in Bonn earlier this year.

When talking about the terms precision and reliability there seems to be a difference in the way these are handled. The photogrammetric approach is to try to model all errors according to a physical model, ending up with many correction terms. The other approach is to model the errors independently of the sources, by e.g. a matrix with a correction vector for each pixel. This latter method is fast and easy to implement, but it is less flexible and more difficult to treat in a statistical context.

A different viewpoint was expressed by one of the system developers when asked about the differences of scientific background, saying something like "...the knowledge of industrial management, how to actually manufacture the system when it is developed and how to get it out on the market. These are things which sometimes are just as important as which algorithm are used for the outer orientation...".

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