# REALTIME POSITIONING OF MOVING OBJECTS BY DYNAMIC TARGET TRACKING

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## Abstract

Positioning and navigation of construction machines are one aim in the Special Research Center on "High Precision Navigation" (Stuttgart). The positioning is done by a system of multiple electronic cameras containing lateral effect photodiodes in the image planes. Two modes of measurement are described: With a minimum of two fixed cameras the positioning is possible in a limited working space. The elimination of reflections and system calibration leads to a high accuracy in object space of at least 1:10000. As an example the dynamic survey of an industrial robot is presented. With electronic cameras mounted on a motorized theodolite the system works as a highly precise dynamic surveying robot for guidance of machines on construction sites. Based on the error theory of the sensor type the dynamic angle measurement properties are developed. This system is a powerful dynamic measurement tool in competition with CCD array based systems and works already with small desktop computers.

## 1. Introduction

Realtime positioning problems are particularly important in the guidance and control process of ship and flight navigation. High speed and position accuracies of several meters are typical for the related time dependent positioning techniques. With the growing tendency to automatic computerised surveying instruments, the high precision navigation for moving objects (p.c. construction machines) leads to new applications for realtime surveying systems in the industrial production and quality control industries. Realtime surveying systems are positioning systems in which the time requirements are minimised so that the running process is not influenced. This means that the measurement frequency depends on the process characteristics which appear slow and have been studied. This can be explained by two examples from civil engineering at the Special Research Center (SFB 228) "High Precision Navigation" in Stuttgart: the test load on a bridge-superstructure must be observed for critical deformations during test loading. The deformation measurement must be fast, so that the unloading may be triggered without delay (in realtime) for security purposes. Another example is the realtime surveying of a tunneling machine. Misalignments during the push forward phase leads to occilations, friction in the tube and unacceptable large jacking forces become necessary. Stereophotogrammetry and point intersection with theodolites are well known traditional surveying techniques providing high accuracy but requiring time consuming computations. With the development of opto-electronic sensors and motorized theodolites these methods are now incorporated with high speed computational systems providing the capability to measure and control moving objects in realtime. Indeed it should be apparent that these two techniques are merging and the development of a new generation of realtime surveying systems is advancing. For high precision navigation of moving objects a modular dynamic surveying system was developed by members of the SFB 228. This paper describes the development and accuracy analysis of the Opto-electronic Position Measurement system (OPM). In combination with a motorized theodolite a dynamic target tracking system for realtime surveying of active targets is performed. The electronic cameras are equipped with lateral-effect photodiodes. In difference to the well-known CCD-sensor cameras with large image processing systems and the time consuming techniques of object identification and extraction, the OPM needs only a light emitting target (p.c. LED). In many cases in the navigation of construction machines, this active target is cheaper than a large computer facility. The OPM can be used in a mono- or stereophotogrammetric mode or in combination with a motorized theodolite as a tracking system. The main problem with realtime surveying by OPM is the reflex-elimination. With suitable reflex elimination techniques positioning with frequencies of several kcps may be achieved.

## 2. Description of sensor-techniques

The key element of the electronic cameras is a lateral effect photodiode (PSD-Sensor), which is located in the image plane and replace the conventional analog film. An active light source, representing geometrically a point in the object space, is imaged on the image plane via a common lens. The principle of the PSD-Sensors can be described as follows (Figure 1).

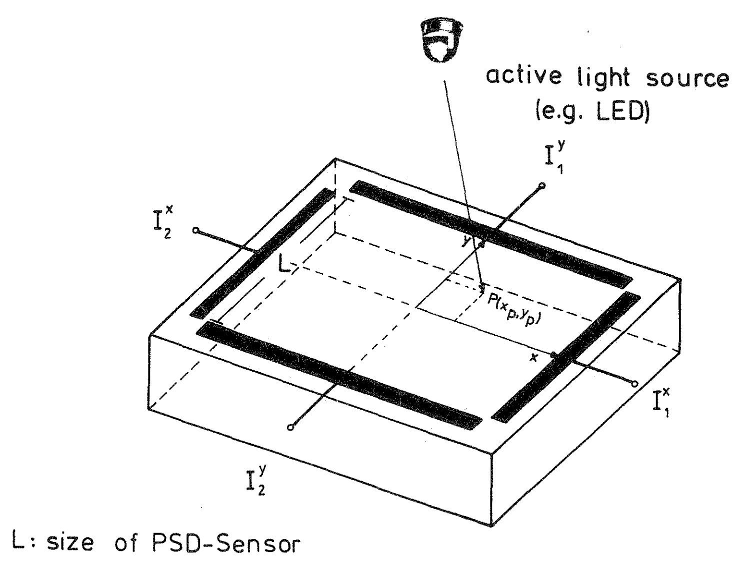



Figure 1: Tetralateral PSD-Sensor

Due to the physical inner photo effect and lateral effect, the radiation of an active light source produces current at four electrodes. The difference of currents of two opposite electrodes is a measure of the position of the projected light source on the sensor surface. In practice it is common to introduce a value for the sensor coordinates with

$$x_p = \frac{L}{2} \frac{I_1^x - I_2^x}{I_1^x + I_2^x}$$

$$y_p = \frac{L}{2} \frac{I_1^y - I_2^y}{I_1^y + I_2^y} \qquad (1).$$

Due to the nonlinearity of the currents $I_k^{x(y)}$, the sensor coordinates in (1) have a high sensor-specific distortion ranging between 0,1 %-10 % depending on the sensor type, operating mode and spot position. Additionally the currents of the sensor correspond to the center of the light spot (Janocha, Marquardt), so that irregularities and disturbances of the light intensity cause imaging errors in the whole imaging system. By pulsing this LED light source and using specially designed optical filters, steady background illumination will not affect the measurement precision. The influence of reflections of the targets on reflecting surfaces, however, still remain.

The advantages of the PSD-sensors are the high dynamic characteristics of about 10 ns in rise time and high position resolution of less than 1µm. If a fast analog-to-digital (A/D) converter with sufficient resolution (e.g. 14-16 bit) is used, a PSD-sensor-based electronic camera is well suited for a realtime measurement system, having excellent dynamic characteristics. For high precision applications the sensor distortion must be calibrated and the reflections thoroughly eliminated by flexible calibration functions and measurement techniques.

Compared to the well known CCD-Sensor and corresponding measurement systems this sensor technique requires manipulation of a very small amount of data. Assuming 32 bit computer, only 4*32 bit per camera are necessary to compute the coordinates of a projected target point in (1). Instead of the complicated algorithms in CCD array cameras, which require processing of 16000 times more data, the image processing in a PSD camera is only a simple evaluation of light intensity of light sources mounted on selected object points. Due to the high dynamics of the PSD-Sensors, multipoint processing of the light intensity becomes feasible by time-multiplexing of several light sources. Indeed, the sensor-specific simplification of the light intensity processing is the reason for the excellent dynamic characteristics of a PSD-camera and is also a distinguishing feature between it and the more intelligent but complex digital computer vision systems.

## 3. Opto-electronic position measurement system (OPM)

### 3.1 Hardware configuration

PSD-sensor-based 3D-measurement systems were first developed and applied in biomedical engineering for human motion study (e.g. Woltring; Conati) and in dynamic analysis of lightweight structures (Kirschstein). These works demonstrate, that realtime 3D-measurement is possible within 0,1-1 kcps. Due to low resolution of the 10-12 bit A/D converters and the reflections of the light sources being not eliminated, these PSD based realtime photogrammetric systems attained the absolute accuracy of 0,05-1 % under optimal conditions.

Our system developed consists of at least two OPM-cameras with 10*10 mm2 and 18*18 mm$^2$ tetra-lateral UDT-photodiodes, high powered infrared CQX 19 LEDs, a telemetered 14 bit data acquisation system and a desktop computer of the HP 200/300 series. The system is capable of computing 3D-positions with 25 Hz in realtime. Initial bench mark tests with a μVAX showed that an improvement by a factor of 10 is easily to be attained. For reflection elimination a special rotating diaphragm in the optical imaging system was installed (Bayer, Krzystek). Figure 2 shows the principle of that special technical part of the OPM.

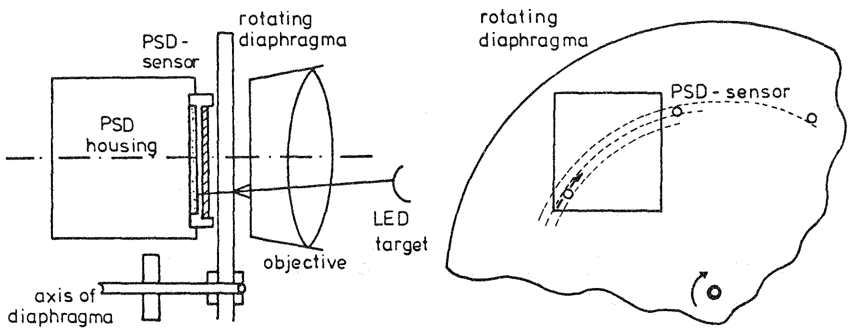



Figure 2: Rotating diaphragm for reflex elimination.

Experiments showed that reflections could be eliminated with an accuracy of 1 - 2 micrometers in the image plane. That is an considerable improvement, because positioning by recently known PSD camera systems were heavily influenced by undetected reflections. This technique of reflex elimination seems to be an operational method. Therefore, the characteristic parts of the OPM-system are the PSD-based OPM cameras, which are insensitive for reflexes. Figure 3 shows the above mentioned entire hardware configuration for 3D-measurement of construction machines.

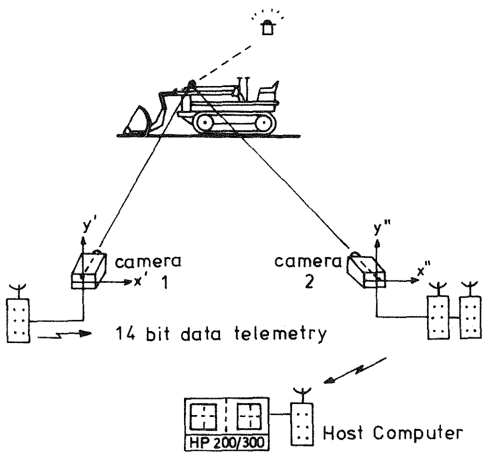



Figure 3: Hardware configuration

## 3.2 Mathematical Model

Projection of a light source by electronic cameras may be described by the well-known (e.g. Schwidefsky, Ackermann) colinearity equations. Systematic errors of sensors, electronic equipment and optical imaging system are compensated by a suitable set of parameters as described below.

$$x_i - x_o = -c \frac{A_{11}(X_i - X_o) + A_{12}(Y_i - Y_o) + A_{13}(Z_i - Z_o)}{A_{31}(X_i - X_o) + A_{32}(Y_i - Y_o) + A_{33}(Z_i - Z_o)} + dx(\underset{\sim}{\alpha}, \bar{x}, \bar{y})$$

$$y_i - y_o = -c \frac{A_{21}(X_i - X_o) + A_{22}(Y_i - Y_o) + A_{23}(Z_i - Z_o)}{A_{31}(X_i - X_o) + A_{32}(Y_i - Y_o) + A_{33}(Z_i - Z_o)} + dy(\underset{\sim}{\beta}, \bar{x}, \bar{y}) \quad (2)$$

where

$\alpha, \beta \cdots$ are the self-calibrating parameters of the electronic camera.

The correction functions are given by

$$dx(\underset{\sim}{\alpha}, \bar{x}, \bar{y}) = a_1\bar{x}^2 + a_2\bar{x}^3 + a_3\bar{x}^5 + a_4\bar{x}^7 + \sum_{m=1}^{3} \sum_{n=1}^{m} b_{mn}\bar{x}^{m-n+1}\bar{y}^n$$

$$dy(\underset{\sim}{\beta}, \bar{x}, \bar{y}) = A\bar{x} + B\bar{y} + c_1\bar{y}^2 + c_2\bar{y}^3 + c_3\bar{y}^5 + c_4\bar{y}^7 + \sum_{m=1}^{3} \sum_{n=1}^{m} d_{mn}\bar{x}^{m-n+1}\bar{y}^n$$

with

$\bar{x} := x_i - x_o$

$\bar{y} := y_i - y_o$

for compensation of non-perpendicularity, scale differences (A,B), lens distortion and sensorspecific errors ($a_i, b_{ij}, c_i, d_{ij}$). The least-squares estimation of the orientation and calibration parameters $\underset{\sim}{u}^T = [\omega, \varphi, \chi, X_0, Y_0, Z_0, x_0, y_0, c, \underset{\sim}{\alpha}^T, \underset{\sim}{\beta}^T]$ and the object coordinates $\underset{\sim}{X}_m^T [X_m Y_m Z_m]$ of an unknown object point $P_m$ is split up in space resection and intersection. The ground control for orientation and calibration is represented by a known calibration frame. Krauss (1983) has shown numerically that his 2-step-solution has no significant decrease in accuracy compared to the closed solution, presuming that sufficient object ground control is available. The stochastic model is considered to be of unit matrix type despite the fact that physical correlations exist caused by the sensor and the electronic equipment.

## 3.3 Calibration

Due to the high 14 bit A/D-resolution, the local systematic sensor distortion caused by irregularities of the sensor substrate can be sufficiently compensated. The polynominal correction functions chosen in (2) are too inflexible to compensate for all the systematic errors with respect to the noise level. After a bilinear interpolation of the systematic errors, a mean standard error of the residuals in the image plane of 3 micrometers remains within a sensor filed of 6*6 mm². Figure 4 and 5 show a three dimensional plot of the image distortion, and the interpolation error after self-calibration with (2) and a bilinear interpolation.

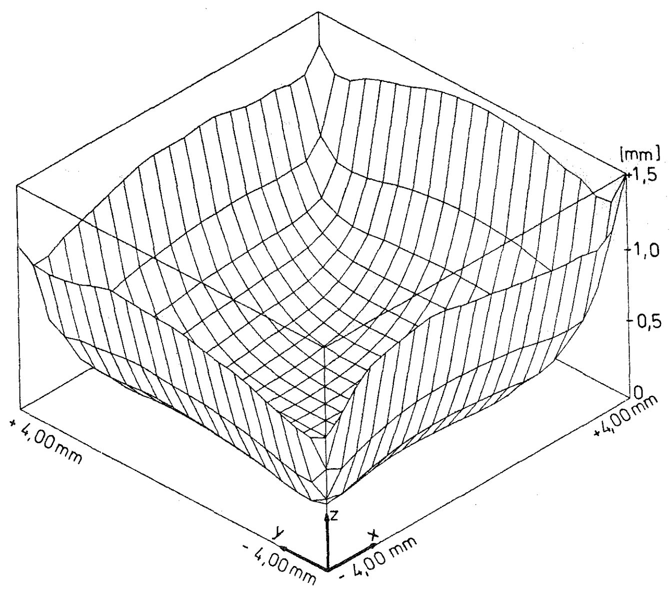



Figure 4:
Sensor distortion

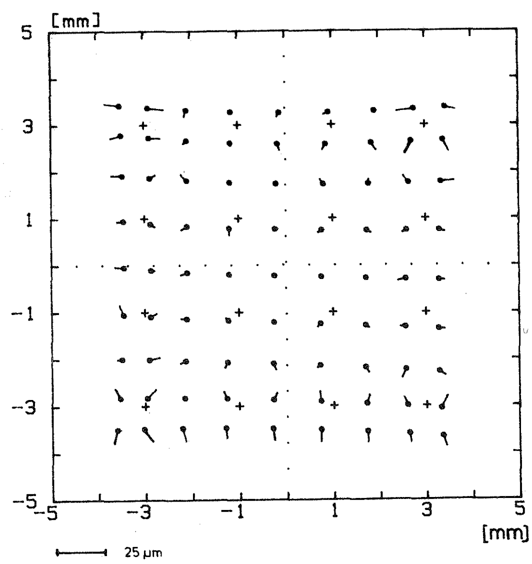



Figure 5:
Interpolation errors

The use of more linear duolateral PSD-sensors or flexible two-dimensional spline functions provides a better calibration accuracy of about 1 micrometer.

## 3.4 Practical experiment

The above mentioned measurement system was applied in the static and dynamic survey of an industrial robot. Robotics become more and more interesting as an application area of stereophotogrammetric techniques. Due to recent advances in the development of opto-electronic sensors, CCD- and PSD-sensors have enabled this traditional surveying technique to become on-line and suitable for realtime applications. From a general point of view a non-contacting measurement technique with a high accuracy, high resolution and realtime characteristic is essential for surveying, calibration and controlling of robots. Besides other existing methods for robot surveying, such as laser trakking (e.g. Hof, Pfeifer), a photogrammetric system with OPM-cameras has the advantage of excellent on-line and realtime capabilities together with high resolution. Figures 6 and 7 show an industrial robot with the calibration frame used as well as the camera locations for the robot survey.

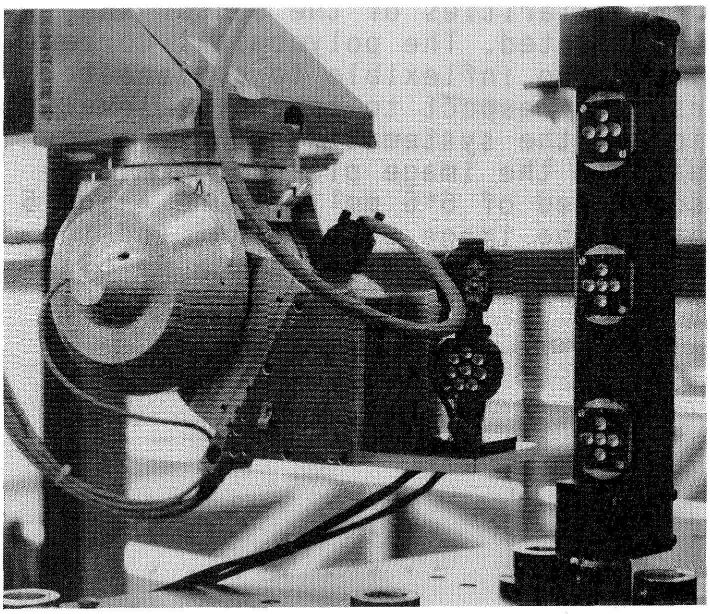


Figure 6: Industrial robot and the calibration frame

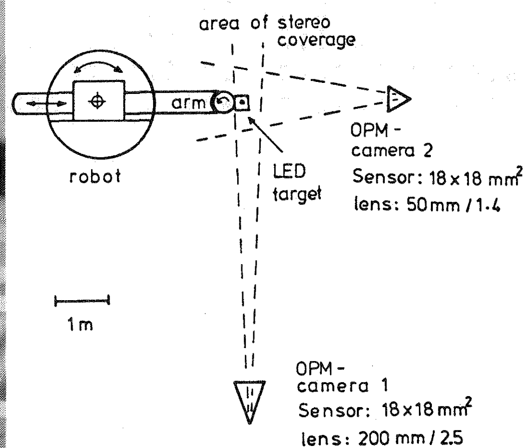



Figure 7: Camera locations for robot survey

With the OPM-system the accuracy of the calibration frame of +/- 0,2 mm was easily attained. Figure 8 shows the trajetory measured of a robot moving with a velocity of 400 mm/sec. The reference curve programmed was a circle defined by the three teach points indicated.
Experiments under optimal laboratory conditions even showed accuracies of about 1:50000. In alignment mode, the OPS-system could significantly measure deviations from a straight line of less than 10 micrometers in object space. These considerably good results demonstrate the performance of the OPM-system for high precision dynamic positioning in close range areas.

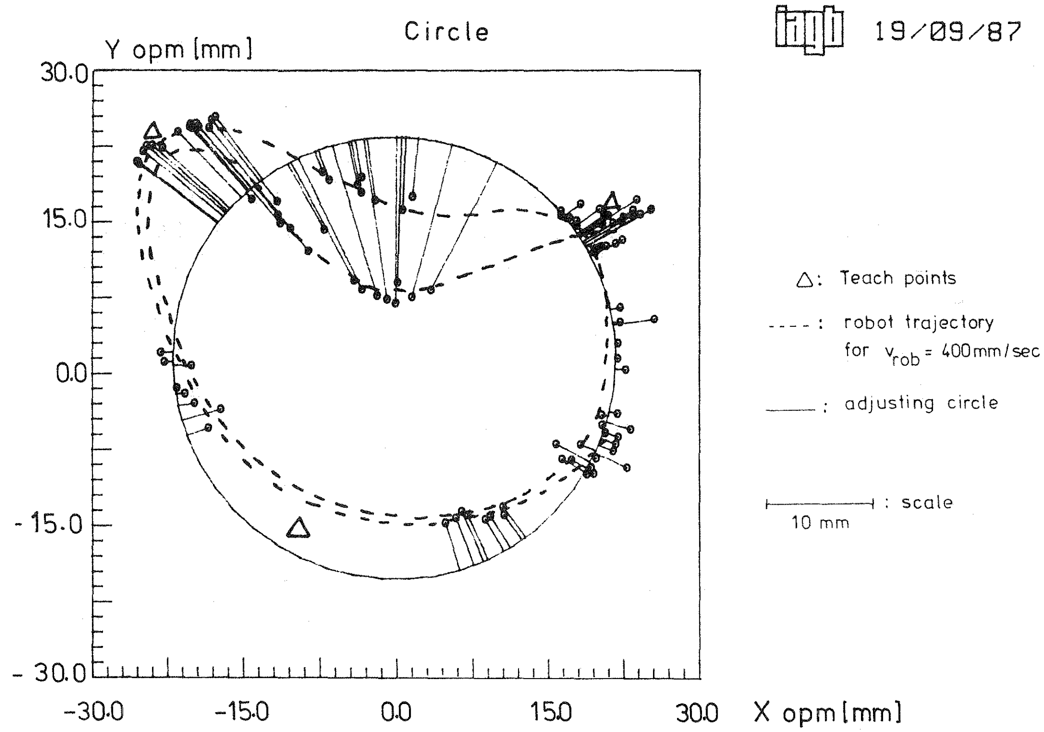



Figure 8: Measured trajectory of a robot moving with a velocity of 400 mm/sec.

## 4. Target tracking by moving cameras based on motorized theodolites

Examples for automatic angle measurement systems based on motorized theodolites and target focussing systems are the GEO-ROBOT-System (Kahmen) and Krupp-Atlas POLARFIX (Meiswinkel). The only known real dynamic system is the MINILIR-System (SAT) with angular velocities up to 100°/sec. The main disadvantage of this system is the high price. The chance to reach an economic level in surveying with Minilir is rather poor. The OPM-camera presented before can be used as target-focussing system by adapting the OPM-camera to the motorized theodolite WILD T2000 MOT. A computer-controlled positioning system with high precision target tracking properties is performed. The accuracy may be demonstrated by the so achieved standard diviation of 0,6 arcsec of focussing a non-moving target. A set of LEDs is used as target for the automatic tracker. The aim of the research work in the SFB 228 is the automatic guidance and control of construction machines within accuracies of several cm or mm. So the topic is the dynamic tracking of moving objects within an angular accuracy of 10 arcsec.

### 4.1 Target tracking

Fixed cameras have a limited measurement range depending on the focal length of the objective and the sensor size. For many applications, e.g. robot surveying, the range of object movement is physically limited and the use of fixed cameras is an effective and cheap alternative. The accuracy of a fixed camera system decreases with an increasing range of object movement, due to the sensor non-linearities near the edges of the sensing surface, the loss of resolution, and the influence of disturbing light.

Tracking systems enlarge the range of object movement without affecting the imaging system properties and thus avoiding the sensor distortions mentioned above. This simplification of the sensor operation results in the occurence of a variable camera orientation, which must be measured with high precision. A theodolite is a very precise instrument for determination of angles. The mechanical adaption of the electronic camera (OPM) presented above to a motorized theodolite is the realisation of an automatic tracking system, consisting of:

1) horizontal and vertical drives
2) horizontal and vertical angle measurement systems,
3) interfaces to communicate with a computer, and
4) an optical sensor as target focussing system. (Fig. 9).

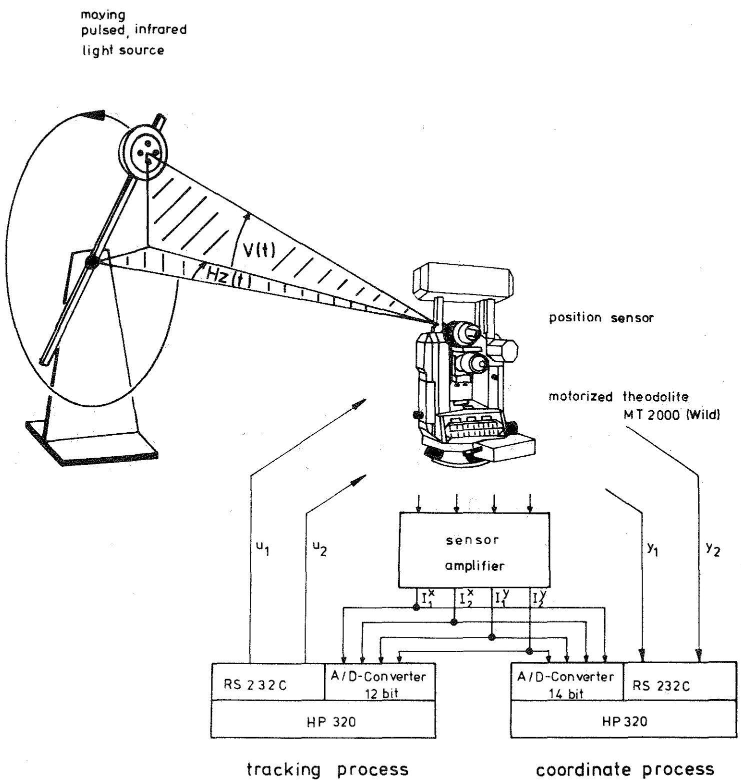
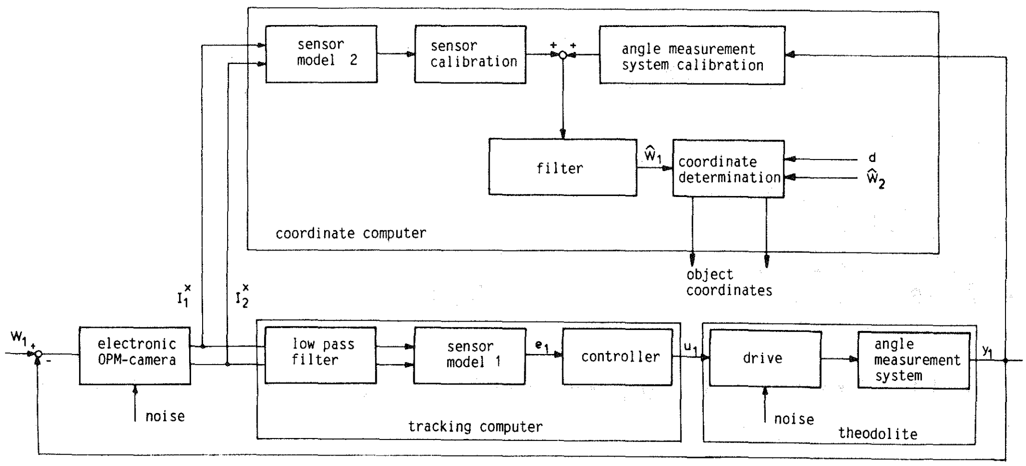



Figure 9: Target tracking system

Our tracking system developed focusses a 1000 cps pulsed infrared light source. The angle measurement is divided into two parallel processes, both with differing requirements - the trakking process which has high dynamic requirements, and the coordinate process requiring high accuracy.
Both processes require amplified sensor signals - the former to compute actuator signals $u_i$ in order to adjust motor revolutions and the latter to determine the angles of the target mark.
Each process utilies a separate computer and different

interfaces depending on the requirements relative to dynamics and accuracy.
The block diagram (Fig. 10) shows the various moduls of the system, and the information flow between them. Seen from a control engineering prespective the goal of a tracking system is to reconstruct unknown reference variales $w_i$ by determining deviations $e_i$ and controlled variables $y_i$ in a closed control loop.
The control of the vertical and horizontal axes is realized as two completely separate processes. The two controllers must eliminate the influences of the mechanical coupling during movement.




$w_1$ ... reference variable (target angle)
$e_1$ ... deviation (sensor angle)
$u_1$ ... manipulated variable (motor voltage)
$y$ ... controlled variable (theodolite angle)
$I_1^x$, $I_2^x$ ... sensor voltage
$w_{1,2}$ ... estimated reference variables
d ... distance between image and target moving plane

Figure 10: Block diagram of a tracker axis

The tracking process consists of three hardware moduls - the electronic OPM-camera, the tracking computer, and the theodolite as control system. The OPM-camera delivers image position signals. The tracking computer filters digitally the high frequency noise of these signals and determines an image coordinate which is actually proportional to the deviation from the target angle.
The controller has to calculate an manipulated variable $u_1$ depending on the deviation. The properties of the tracking process comprising stability and guidance are influenced by the design of the controller. The reconstruction of the reference variable is based on the accurate determination of the deviation and the controlled variable $y_1$. High accuracy is attained by improving the sensor model, calibrating the non-linearities of both measurement systems, and using optimum filtering methods. This tracking process is performed for the horizontal and vertical axes of the motorized theodolite. Together with distance measurement it is possible to compute the object coordinates of the target.

## 4.2 Accuracy of the tracker

The design of the controller is the first step towards operation of this tracking system presented. The maximum speed of the target and the deviation of the line of site to the actual target position depend on the dynamics of the tracking process. The second step is to examine the coordinate process in relation to the type of errors, present quantities of errors, and their elimination. Fig. 11 shows the standard deviation of the remaining errors. These arrors can be minimized successfully by improving electronic amplification, calibration and filtering resulting in a high precision angle measurement system.

| type of errors | standard deviation horizontal | (mgon) vertical |
|---|---|---|
| 1) deviation measurement | | |
| - non-linearity | 10 | 10 |
| - noise | 30 | 30 |
| 2) controlled variable measurement | | |
| - non-linearity | 24 | 7 |
| - free motion | 0,6 | 7 |

Figure 11: Errors of determinating angles of the target

The third step is to improve the accuracy of the whole system. For that purpose we designed a motion simulator with a predetermined trajectory. 5 LEDs are attached to a motor-driven, rotating arm. (Fig. 9). The arm movement describes a circle with a radius of 1 m.
From a distance of three meters, angular velocities up to 20 °/sec. are now achievable. Thus regarding the circular motion is difficult in sense of the tracking process.

Due to the orientation of the tracker with respect to the rotating arm, the target describes an ellipse as seen by the trakker. We thus obtain an information of accuracy by fitting an ellipse to the calculated object coordinates and determining the standard deviation.
With a maximum frequency of 0,02 cps and angular velocities of the tracker of 2,6 °/sec. we obtain an accuracy of +/- 80 arcsec and +/- 1,5 mm relative to the adjusted ellise coordinates. The aims of further research are the improvement of accuracy and the realisation of the system in its intended application, i.e. the control of construction machines.

## 5. Conclusion

With the OPM-realtime surveying system a high dynamic and precise target tracking modul is available. First tests for dynamic positioning in the SFB 228 "High Precision Navigation" (Stuttgart, D) demonstrated the performance of this equipment. For close range surveying problems this positioning system may become a useful tool in surveying engineering and industrial mensuration.

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