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COMPUTER SCIENCE MEETS AUTOMATION

VOLUME I

Session 1 - Systems Engineering and Intelligent Systems

Session 2 - Advances in Control Theory and Control Engineering

Session 3 - Optimisation and Management of Complex Systems and Networked Systems

Session 4 - Intelligent Vehicles and Mobile Systems

Session 5 - Robotics and Motion Systems

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Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.
- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.
- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.
- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.
- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.
- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52nd International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.
I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.

Professor Peter Scharff
Rector, TU Ilmenau

Professor Christoph Ament
Head of Organisation

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Ch. Wachten / Ch. Ament / C. Müller / H. Reinecke

Modeling of a Laser Tracker System with Galvanometer Scanner

INTRODUCTION

Laser trackers are systems that are capable of doing high accuracy 3D measurements. A laser beam is deflected by an actuator and follows the movements of a reflector in space. The position of the reflector can uniquely be defined by the distance measurement of an integrated interferometer and the measurement of the angle encoders of the actuator. Such systems offer the possibility of doing static as well as dynamic measurements. That is the reason why they are used in calibration tasks e.g. for robots or for coordinate measurement machines [1], [2].
In this paper we present a laser tracker system that is based on a galvanometer scanner. The accuracy of the system depends on the model as well as the calibration algorithm. Therefore a complete analytical model is developed that takes into account the internal behavior of the system and calculates the transformation of the measurements into 3D coordinates. An inverse kinematics is also developed to have the possibility to simulate the calibration process to reduce time and cost consuming experiments.

OPERATION PRINCIPLE OF THE LASER TRACKER SYSTEM

Fig. 1 shows the operation principle of the laser tracker system. A two-frequency HeNe laser emits two slightly different frequencies. The split frequency is about 2 MHz. An interferometer splits the laser beam into a reference beam (frequency f_2) and a measurement beam (frequency f_1). The measurement beam leaves the interferometer hits a non-polarizing beam splitter and is deflected by a magnetically driven actuator and is reflected by a retroreflector in space. On its returning path the reflected beam again hits the beam splitter and the beam position is analyzed by a quadrant diode. A part of the beam also interferes with the reference beam in the interferometer.
The quadrant diode generates analog output signals which are the inputs of a subsequent analog PI controller. This controller deflects the mirrors of the actuator in such a way that the laser beam follows the movements of the reflector. If the reflector is moved, the laser beam leaves its initial position – ideally the center position - on the quadrant

diode and the controller compensates the deviation. The controller has to be fast because the offset between the reference beam and the measurement beam must be below a certain threshold value to guarantee a stable function of the interferometer. With an analytical model the position of the reflector can be calculated. So, a direct kinematics is needed which transforms the angle and distance measurements into real coordinates.

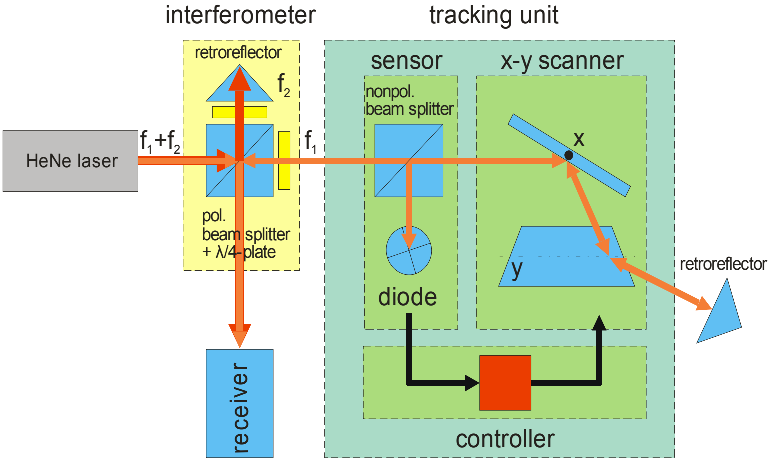

Fig. 1. Operation principle of the system

DEVELOPMENT OF THE DIRECT KINEMATICS

The analytical model of the system is an essential part because it is responsible for the accuracy of the system. It is important to consider all effects in contrast to [3] in the interferometer-scanner head to obtain a good model. First the interferometer function is neglected and the laser beam is propagated through the scanner head as proposed in [1]. So, the direction of the outgoing beam can be written as a line as shown in (1).

$$\vec{g}_{S1} = \overrightarrow{OC} + s \cdot \vec{r}_{S1} \tag{1}$$

The point C, the direction $\vec{r}_{S1}$ and the parameter *s* have to be calculated (see Fig. 2). The direction is $\vec{r}_{S1}$ obtained by a reflection of $\vec{r}_L$ on the second mirror resulting in $\vec{r}_{S21}$ and a reflection of $\vec{r}_{S21}$ on the first mirror resulting in $\vec{r}_{S1}$. The normal vectors of the mirrors depend on the rotation of the corresponding axis. This is modeled by the Rodrigues formula given in (2) and (3).

$$\boldsymbol{R} = \begin{pmatrix} v_x^{\,2} \cdot A + \cos\alpha & v_x \cdot v_y \cdot A - v_z \cdot \sin\alpha & v_x \cdot v_z \cdot A + v_y \cdot \sin\alpha \\ v_x \cdot v_y \cdot A + v_z \cdot \sin\alpha & v_y^{\,2} \cdot A + \cos\alpha & v_y \cdot v_z \cdot A - v_x \cdot \sin\alpha \\ v_x \cdot v_z \cdot A - v_y \cdot \sin\alpha & v_y \cdot v_z \cdot A + v_x \cdot \sin\alpha & v_x^{\,2} \cdot A + \cos\alpha \end{pmatrix} \tag{2}$$

$$\text{with } A = 1 - \cos\alpha \tag{3}$$

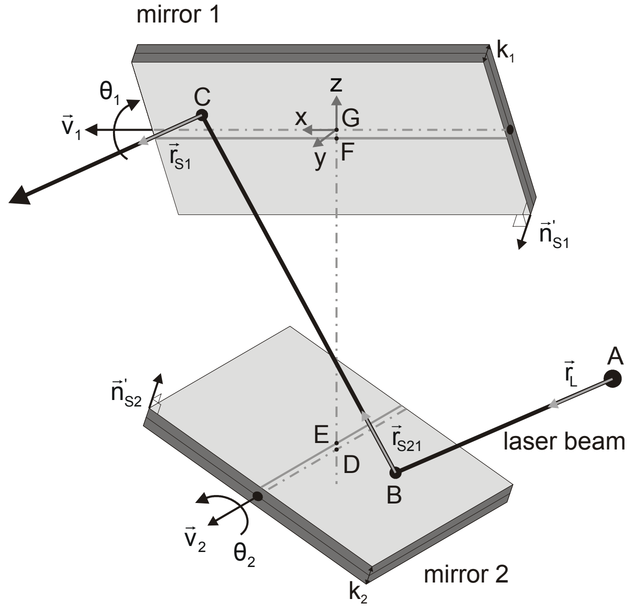

Fig. 2. Beam propagation through the scanner head

The vector $v_i = (v_x, v_y, v_z)$ in the matrix describes the direction of the rotation axis of the mirrors and α represents the rotation angle. With the updated normal vector in (4)

$$\vec{n}'_{Si} = \boldsymbol{R}(\vec{v}_{\boldsymbol{i}}, \theta_i) \cdot \vec{n}_{Si} \tag{4}$$

and the law of reflection the direction $\vec{r}_{S1}$ is calculated in (5).

$$\begin{aligned} \vec{r}_{S1} &= \vec{r}_{S21} - 2 \cdot (\vec{n}'_{S1} \cdot \vec{r}_{S21}) \cdot \vec{n}'_{S1} \\ &= (\vec{r}_L - 2 \cdot (\vec{n}'_{S2} \cdot \vec{r}_L) \cdot \vec{n}'_{S2}) - 2 \cdot (\vec{n}'_{S1} \cdot (\vec{r}_L - 2 \cdot (\vec{n}'_{S2} \cdot \vec{r}_L) \cdot \vec{n}'_{S2})) \cdot \vec{n}'_{S1} \end{aligned} \tag{5}$$

To obtain the point B, the line with its starting point A and the initial direction $\vec{r}_L$ is cut with the mirror plane of the second mirror. Point B is calculated in (6).

$$\overrightarrow{OB} = \overrightarrow{OA} + \frac{(\overrightarrow{OD} + u_2 \cdot \vec{n}'_{S2} - \overrightarrow{OA}) \cdot \vec{n}'_{S2}}{\vec{r}_L \cdot \vec{n}'_{S2}} \cdot \vec{r}_L \tag{6}$$

To obtain point C the line with starting point B and direction $\vec{r}_{S21}$ is cut with the mirror plane of the first mirror.

$$\overrightarrow{OC} = \overrightarrow{OB} + \frac{(\overrightarrow{OG} + u_1 \cdot \vec{n}'_{S1} - \overrightarrow{OB}) \cdot \vec{n}'_{S1}}{\vec{r}_L \cdot \vec{n}'_{S1}} \cdot \vec{r}_{S21} \tag{7}$$

The parameter $u_i = k_i / 2 + a_i$ describes the distance between the model point of the rotation axis and the mirror plane. The parameter k_i represents the thickness of the mirrors and the parameter a_i is used to model a dumping of the mirror plane to the rotation axis. Now the interferometer function is considered. It is modeled with the parameter s of the line in (1). The interferometer only measures relative distances to a given point. It is assumed that the retroreflector is put to a special point with known angles θ_{1start} and θ_{2start} and the initial length r_0 as shown in Fig. 3a). If the reflector is moved from point P_1 in Fig. 3b) to point P_2 then the interferometer detects a change in length that does not correspond to the length Δr because the beam path in the scanner head is neglected.

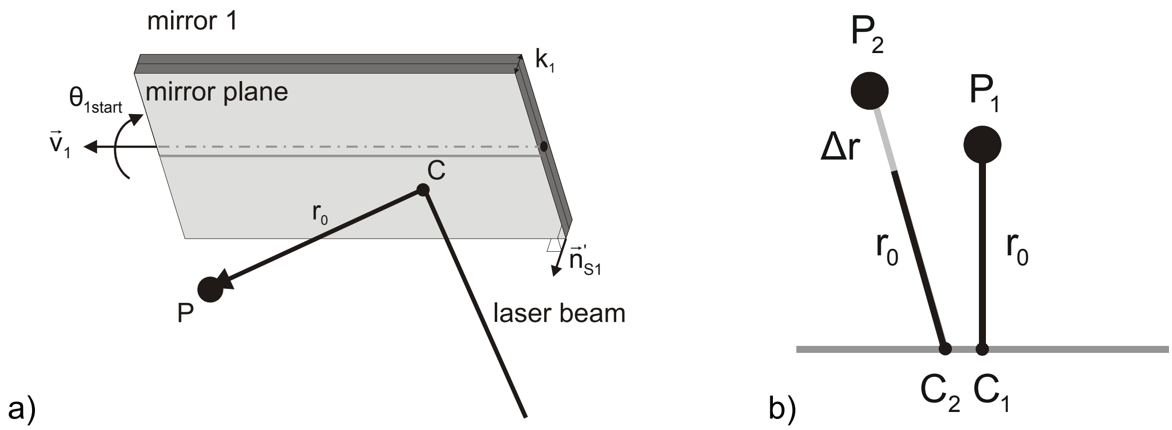

Fig. 3. Start condition a) and relative measurement of the interferometer b)

To overcome this problem the rotation angles of the mirrors have to be considered. So, it can be written for the parameter *s*:

$$s = r_0 + \Delta r_{gem} - \Delta AB - \Delta BC \tag{8}$$

with

$$\Delta AB = |\overrightarrow{OB}(\theta_2) - \overrightarrow{OA}| - |\overrightarrow{OB}(\theta_{2Start}) - \overrightarrow{OA}| \tag{9}$$

$$\Delta BC = |\overrightarrow{OC}(\theta_1, \theta_2) - \overrightarrow{OB}(\theta_2)| - |\overrightarrow{OC}(\theta_{1Start}, \theta_{2Start}) - \overrightarrow{OB}(\theta_{2Start})| \tag{10}$$

So, the outgoing laser beam is completely defined through its point C and its direction $\vec{r}_{S1}$ and the parameter *s*. It is also of interest to calculate the inverse kinematics because a calibration algorithm can be tested without real experiments.

DEVELOPMENT OF THE INVERSE KINEMATICS

The inverse kinematics calculates to each reflector point in space the angles of the actuator and the distance of the interferometer from an arbitrary starting point. First the reflector is put to a point P in space as shown in Fig. 4. The laser beam is assumed to be deflected in space and does not hit the reflector. There is a distance *a* between point P and point F. The distance *a* is calculated in (11). The aim is to minimize this distance so that point P is coincident with point F as shown in (12).

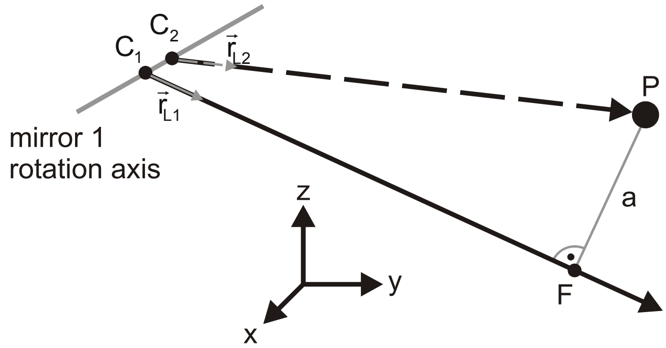

Fig. 4. Method to calculate the inverse kinematics

The angles of the mirrors are calculated with a numerical minimization algorithm implemented in Mathematica 5.2. This can only be done if the parameters of the laser tracker system are known.

$$a = |\overrightarrow{FP}| = |\overrightarrow{OP} - \overrightarrow{OC_1} - \left[(\overrightarrow{OP} - \overrightarrow{OC_1}) \cdot \frac{\vec{r}_{L1}}{\vec{r}_{L1}^{\,2}} \right] \cdot \vec{r}_{L1}| \tag{11}$$

$$a \to 0 \Rightarrow \vec{r}_{L1} = \vec{r}_{L2} \wedge \overrightarrow{OC_1} = \overrightarrow{OC_2} \tag{12}$$

To complete the inverse kinematics the path change during the measurement is considered. Fig. 5 shows the beam path at the beginning of a measurement (black line) and during a measurement (gray line). The starting angles θ_{1start} and θ_{2start} are obtained by minimizing (8). So the points B_{start} and C_{start} are calculated. The relative path change is calculated by considering the system in sections.

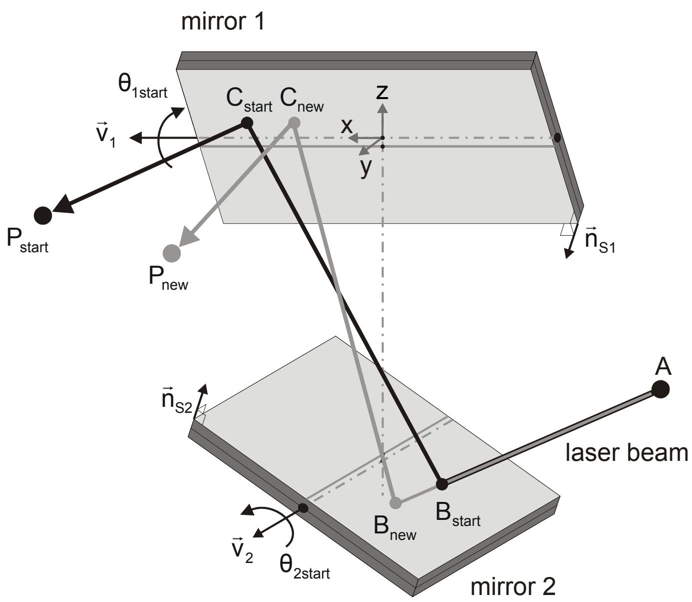

Fig. 5. Beam path at the beginning (start) and during (new) a measurement

The first section describes the path change between the reflector and the point C. The second section describes the path change between the two mirrors and finally in the third section the path change between the incident laser beam and the second mirror is considered. This is resumed in (13).

$$\Delta r = \underbrace{|\overrightarrow{C_{new}P_{new}}| - |\overrightarrow{C_{start}P_{start}}|}_{section\ 1} + \underbrace{|\overrightarrow{B_{new}C_{new}}| - |\overrightarrow{B_{start}C_{start}}|}_{section\ 2} + \underbrace{|\overrightarrow{A_{new}B_{new}}| - |\overrightarrow{A_{start}B_{start}}|}_{section\ 3} \qquad (13)$$

CONCLUSION

We have presented the direct and the inverse kinematics for a laser tracking system with galvanometer scanner. The analytical model covers nearly all effects in the scanner head. Furthermore it is possible with the inverse kinematics to simulate the calibration algorithm and to plan trajectories. This saves time and cost consuming experiments.

References:

[1] J. R. R. Mayer and G. A. Parker, "A Portable Instrument for 3-D Dynamic Robot Measurements Using Triangulation and Laser Tracking", IEEE Transactions on Robotics and Automation, Vol. 10, No. 4, August 1994

[2] H. Gander, M. Vinzce and J. Prenninger, "An external 6D sensor for Industrial Robots", IEEE/RSJ Intelligent Robots and Systems, Yokohama Japan, pp. 975-978, July 1993

[3] J. Wang, Z. Hu, Y. Liu and J. Liang, "Experimental Research on Laser Tracking System with Galvanometer Scanner for Measuring Spatial Coordinates of Moving Target", Proceedings of SPIE - Optical Measurement and Nondestructive Testing: Techniques and Applications, Vol. 4221, pp. 10-14, October 2000

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