A FLEXIBLE AND, ROBUST 3D COORDINATE MEASUREMENT SYSTEM BASED ON WHITE LIGHT INTERFEROMETRY FOR CALIBRATION OF INDUSTRIAL SYSTEMS

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Abstract:
The demand on the precision of machine tools is steadily increasing. In this context, the intrinsic accuracy of the machine tools is no longer sufficient. Nowadays volumetric compensation is applied to minimize the errors of the tool center point.

This paper presents a new, flexible, high precision coordinate measurement system which also offers a great automation potential. Its principle is based on white-light interferometry. The system measures the distance between an emitter and minimum three reflectors. The position of the emitter with respect to the reflectors is determined via multilateration. Therefore, environmental conditions need to be measured and effects like thermal expansion need to be compensated by software. The mathematical and physical models for this compensation have been developed and applied to the system.

Measurements were done under workshop conditions and the results show that the precision of µ-GPS system is comparable to nowadays measurement systems which are used for machine calibrations. Additionally the µ-GPS system allows a high precision 3-dimensional determination of the position. The calibration process can be done fully automated which is completely new in this kind of applications.

Keywords: Intelligent measurement, Coordinate Measurement, Volumetric Compensation, Interferometry

1. INTRODUCTION

Nowadays many devices in our everyday life are desired to become more compact and at the same time more efficient and longer lasting. Manufacturing of such devices requires high quality production process and behind of that very high precision machine tools or industrial robots.

As a base of the machine tools the linear axes of these machines need to be highly accurate. However, the precision of the machine is much worse as the single linear axes due to errors in the assembly of the different components. As a result e.g. the squareness might be not fulfilled. Furthermore, the environmental parameters like temperature at the operation differ from those of the standard for which the machine tool is build and certified. This leads to further deformation of the machine tool and length errors in the linear drive system.

For high precision manufacturing it is necessary to compensate these errors as far as possible. The method of choice is the so-called volumetric compensation [1-2]. In the following, the volumetric compensation and the state of the art methods are described. Based on that, the principle of the µ-GPS system is discussed.

2. VOLUMETRIC COMPENSATION

For the volumetric compensation, a discrete, regular grid of positions of the tool center point (TCP) is gauged with a very precise coordinate measurement system (CMS). The results of the CMS are compared with the programmed grid and for each position an error vector is transferred to the machine control via the interface. Between the points of the grid, the error compensation vector is yielded by interpolation. To minimize errors due to the interpolation, the grid spacing must have an appropriate size. Since decreasing the grid spacing increases the measurement time, a tradeoff has to be made. To minimize the idle time and the variation of the environmental conditions, the CMS has to be fast enough. In principle this compensation can be performed for more than one temperature to account for temperature variations that usually occur over a workday. However, this takes an enormous amount of time. The state-of-the-art methods perform the volumetric compensation will be presented in the following.

3. CONVENTIONAL SYSTEMS

For the certification of a machine tool the linearity of the single axis and the squareness of all pairs of axes are often measured with the aid of a standard, e.g. a granite square. However, the alignment of the reference and the measurement of the distance to the reference via a dial gauge take a lot of time and are very elaborate. Due to the size and weight of the standard, this method cannot be applied in the whole working volume. On the other hand the intrinsic errors of the standard and dial gauge, lack the precision for volumetric calibration.

At the moment only the laser-interferometer systems provide the requested accuracy and measuring volume. These systems, especially Laser Trackers and Laser Tracers determine the length based on laser interferometry. A Laser Tracker system measures one distance and two angles to a so-called target to determine the targets coordinate in space. The length measurement of a laser interferometer offers a very high precision whereas the angle measurement lacks precision especially for long distances. To compensate for the inaccurate angle measurement, the Laser Tracer system measures only distances to determine the position. Therefore the distance to the target is measured from four different positions. This can either be done with four Laser Tracers at the same time or using only one Laser Tracer and measuring four times consecutively. From the determined distances the coordinate can be evaluated by multilateration (see sec. 4.3).

However, also working with these systems brings along some disadvantages. First of all, the acquisition is quite expensive and hence problematic for small companies. Not all Laser Trackers feature an absolute distance measurement (ADM). In this case the length determination works incrementally which means that the disruption of the laser beam results in the loss of the fringe count and the complete measurement has to be repeated. Additionally the collimated laser beam favors a disruption of the beam. Also the accuracy at smaller distances is not high enough for using the Laser Tracker systems to compensate and calibrate e.g. machine tools in. Finally none of these systems allows an automated calibration process in the time consuming machine acceptance phase.

4. µ-GPS SYSTEM

4.1 History

The µ-GPS system was developed within the context of ACCOMAT project of the Federal Ministry of Education and Research (BMBF). The original idea was to use the system as measurement system of linear axes for machine tools. As a result of the ACCOMAT project it was determined that principle of the µ-GPS works reliably but the system allows just high accuracy at low measurement rates. However machine tools require measurement rates around 10 kHz which could be not realized with µ-GPS system. In a following project a new application of the µ-GPS was analyzed [3]. The intention was to use the system for applications where low measurement rates can be accepted. This is the calibration of machine tools, robots or automated systems. Based on this work the µ-GPS Optics GmbH was founded as a spin off in 2007 to adapt the system for the industrial market.

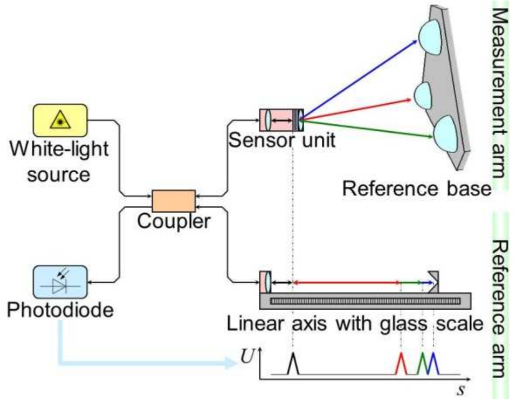

Fig 1: Working principle of the µ-GPS system.

4.2 Working Principle

The system is based on white-light interferometry. This principle employs a light source with a small band width of about $\Delta\lambda = 100$ nm and a small coherence length of $\zeta < 100$ µm. In the whole-fiber-based setup, the light is split into two beams of which one is guided to the reference arm of the interferometer and the other to the measurement arm (see figure 1). The used beam splitter is asymmetric. In the system it is favorable to couple 90% of the light to the emitter since a lens system couples the light to free space with a total opening angle of 60°. The light is reflected by minimum three cat's-eye retro-reflectors with an acceptance angle of about 60°. The reflected signal is coupled into the fiber by the lens system which also serves as a receiver and is guided back to the beam splitter.

The other 10% of the signal of the light source are guided to the reference arm where the beam stays collimated. It contains basically a moveable mirror, i.e. a reference run. Both the light reflected in the measuring arm and in the reference arm are superimposed at the beam splitter and guided to a photo diode. Due to the short coherence length an interference signal is only detected at the photo diode if the optical path in the measurement arm and reference arm is the same. The length is read out with micron resolution at a glass scale in the reference arm. Note that the reference arm is placed in an extra compartment within the control unit which is decoupled from the rest of the electronics and thermally stabilized and vibration damped to guarantee an accurate length measurement.

4.3 Position Measurement

The small emitter is usually placed at or close to the TCP of the machine tool and thus at the point of interest. The reference base can be placed freely in the working volume of the machine. Both the emitter und the reference base are connected with control unit by armored cables and fibers, respectively.

Similar to the global GPS system where the position of an object on the earth surface is determined by three or more satellites, the position of the emitter with respect to the reference base can be determined by the measured distances via trilateration.

$$(x-u_i)^2 + (y-v_i)^2 + (z-w_i)^2 = L_i^2 \qquad (1)$$

Where x, y, z are the coordinates of the emitter and u_i, v_i and w_i are the coordinates of the ith retro-reflector. The quantities L_i denote the geometrical distance between the ith reflector and the emitter. With three reflectors the position can be determined. Of course more than three reflectors can be used. In that case, the position can be determined more accurately and the overestimated system of equations is solved using an iterative least square algorithm with estimated positions [4]. In principle it is also possible to determine the orientation at the TCP. Therefore, the system has to be modified to measure with three emitter and three reflectors.

4.4 Measure to increase the accuracy of the µ-GPS

Over the last years the µ-GPS Optics GmbH worked continuously on increasing the accuracy.

Considerable work has been done on the signal evaluation. Filters were improved to enhance the signal-to-noise ratio (SNR). For the evaluation of the signal position a convolution method showed best results. Here, a pattern *g(x)* is moved over the measured signal *f(τ)* and the convolution integral is calculated.

$$(f * g)(x) = \int_{\mathbb{R}} f(\tau)g(\tau - x)d\tau \qquad (2)$$

If pattern and signal are on top of each other the integral has its maximum and the position is found. This method is advantageous because even a very weak signal can be found since the shape of the peak plays an important role.

It is important to note the length L_i read from the glass scale is the optical length P_{opt}. This quantity contains the refractive indices of the different media the light passes, i.e. the cat's-eye retro-reflectors n_g and air n_a. The length does not coincide with the geometrical distance L which is needed for the multilateration. The deduction of geometrical length from the optical length is crucial for the accuracy of the system. The geometrical relation which as the basis of all calculations is:

$$P_{opt} = \sqrt{(L+R)(L+r^2/R)\left(L+n_g^2R/n_a^2\right)/L} \qquad (3)$$

Here, R and r denote the radii of the large and the small hemisphere of the cat's-eye retro-reflector, respectively. Note, that this equation has to be solved numerically.

As mentioned in section 4.2, P_{opt} is determined with µm resolution. Hence, the precision of L_i and by association the coordinate is mostly determined by the accuracy of the values n_a, n_g, R and r since their exact values depend on the environmental conditions. Whereas a lot of research was done on the refractive index of air, (see for example [5]) the behavior of the other materials is not studied so well. The uncertainty in the exact temperature behavior of n_g leads to an uncertainty in the L_i up to a few micrometers. The radii of the hemispheres can be determined very precisely by coordinate measurement machines (CMM). However, these precise values are only valid close to the calibration temperature of the CMM. Away from this temperature, the accuracy of R and r depends on the precision of the temperature measurement and on the knowledge of the linear expansion coefficient α. Since α of the order of 10^{-6} 1/K the resulting uncertainty in L_i is about 1 µm. For the determination of the coordinates the position of the cat's-eye reflectors with respect to each other is needed. They are determined also by a CMM with micrometer precision. Since they are mounted in a common invar frame, their relative position does not depend on temperature. Taken together the uncertainties in the geometrical path lengths result in an uncertainty of the 3D coordinate of about 10 µm.

Therefore, major work was done on the precise determination of the environmental parameters and on the deduction of the geometric length. On the one hand the algorithms for the calculation of the wavelength and temperature dependent refractive index of the optics and the calculation of the geometrical length were revised. Number and placement of all sensors for environmental parameters were also reconsidered. Hereby, the arrangement of the sensors is chosen so that not only the temperature but also temperature gradients in the measurement or reference arm can be detected which, to our knowledge, does not exist in other CMS. Thermal expansion is also crucial for the deduction of the geometrical length. Here, improvements were made on the construction of emitter and reference base. Important parts which contain the sensible optics are made of invar, which has almost no thermal expansion at room temperature [6]. For the other parts less dense materials were used to reduce the overall weight. Thereby special consideration was given to ensure that no stress occurs at the optical elements. Additionally the thermal stabilization of the compartment which contains the light source and the reference arm were improved.

Further improvements were made to increase the measurement speed. The data rate has been increased from 2 MHz to 7 MHz. Therefore, the speed of the linear axis could be increased by a factor of three.

Is the approximate position of the emitter known, the interference signals can be always assigned to the particular reflectors. The aim is to import the path of the machine tool to the µ-GPS software. In this case the measurement can be completely automated. At the same time the measurement speed can in principle be improved considerably in the way that the skid does not have to move over the whole axis every time but only a small part since the approximate position of the signal is known.

The system offers many more advantages:

The divergent light cone and optimized size of the cat's-eye retro-reflectors make the system capable of working in production environment since the system is largely insensitive to interference arising from filings or coolants.

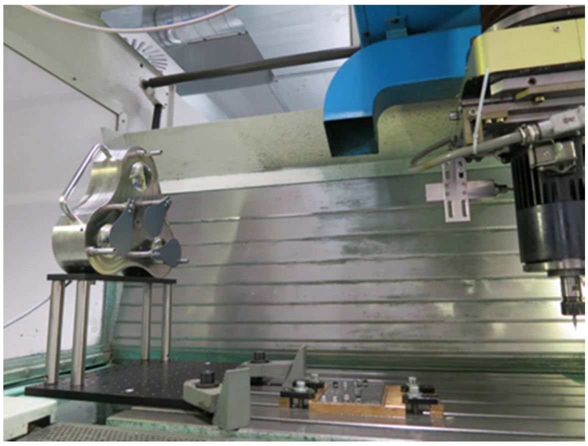

Fig. 2: Mounting of the µ-GPS system on the Mikromat 4S milling machine.

The length measurements are absolute, hence even the loss of one distance will only result in loss of one coordinate. In this case the software automatically remeasures the lost position.

Both the emitter and the reference base which contains the reflectors are easy to handle, thus the integration time is reduced considerably. In all measurements up to now the installation of the system has never taken more than 30 minutes. Figure 2 shows the mounting of the µ-GPS system on a Mikromat 4S milling machine (see sec. 5).

By the size, distance and number of the retro-reflectors the reference base can be customized according to measurement speed, precision or the size of the working volume.

5. RECENT RESULTS

Recent measurements under workshop conditions were carried out on two different machines. First machine was a precision milling machine Mikromat 4S. The machine was programmed to scan a grid. At each position the coordinate was measured three times. The system measured continuously for 16 hours without supervision. The measurement yielded about 2000 data values at ca. 500 positions. Figure 3 shows the measured positions (small dots). The hemispheres on the left side denote the position of the retro-reflectors and the cone denotes the working volume of the µ-GPS system. Due to the position uncertainty of 8 µm of the Mikromat 4S, the data of this measurement was used to create a calibration function for the µ-GPS system to reduce the residual errors.

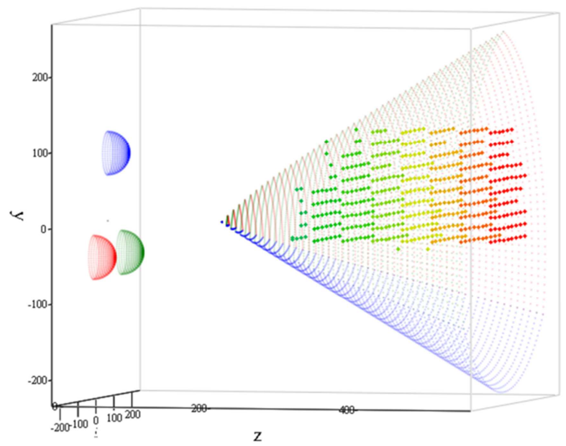

Fig. 3: Visualized measured coordinates at the Mikromat 4S. The cone denotes the working volume of the µ-GPS system.

Employing this calibration function, the µ-GPS system was mounted on the Hexabend machine [7]. However, parallel kinematics does not possess the same accuracy as serial kinematics. Thus parallel kinematics needs to be thoroughly calibrated. For this measurement the µ-GPS system and a Faro Laser Tracker were deployed. Two distinct lines along the z-axis of the Hexabend were measured and the results of the µ-GPS system and the Faro Laser Tracker were compared. It shows that both results agree well within their errors.

6. SUMMARY AND OUTLOOK

The µ-GPS system based on white-light interferometry shows already promising results. A big advantage is the easy implementation and handling of the system associated with the reduced idle time of the machine tool. The system offers a fast, absolute and, contactless determination of the 3-dimensional coordinates in space. Thereby, precision, measurement speed and working volume can be optimized according to the task. The implementation of path traveled by the machine tool into the µ-GPS software offers also a great automation potential. Sensors to measure the environmental conditions are integrated by default and the associated effects are compensated by the software.

Currently the µ-GPS Optics GmbH builds up a second generation of the system based on all experience collected so far. The hardware and software are optimized for measurement speed as well as precision. Desired is to measure one coordinate each second with a spatial accuracy of ±3 µm. Additional the software is modified for the communication with the control of the machine tool. This means the µ-GPS is the first system on market that allows a fully automated calibration process for machine tools by a free programmable path and an automated volumetric compensation procedure.

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