3D interferometric measurement system for machine tool on-line control

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ABSTRACT

We present the definition and development of a three dimensional high precision measurement system for localisation and control of machine tool's drill based on a Michelson-Morley interferometric configuration and a laser tracking subsystem to redirect the measurement beam onto a retro-reflector positioned in the tool nearness. The system measures the retro-reflector position in real time with 5 microns accuracy up to 2 m/s processing material velocities and it is used to carry out an on-line control feedback of the drill position in the machine tool allowing a drill tool replacement during the fabrication process. The system has been integrated and tested in an especially designed machine tool built for this application.

Keywords: Interferometry, metrology, multi-system integration, mechatronic, laser tracking.

1. INTRODUCTION

Machine tools have been used in numerous industrial areas to manufacture a widely range of pieces. Thus, the process precisions and the manufacture speeds must be greater every time to cover the requirements imposed by the market. Until now, the precision in machine tools is conditioned by the measurement system of the axes that produce the mechanization process. In most cases, these measurement systems are based in encoders and optical rulers that have intrinsic limitations due to different factors. Because of the non-measuring fact in the mechanization point there are quasi-static errors as temperature gradients, insufficient mechanical stiffness and so on. Others depend to the axis layout and are called static errors: scale mounting errors and lack of orthogonality errors (roll, yaw, pitch). Finally, another kind of errors related with the natural oscillations in the machine and with elastic deformations due to inertia and process forces are present during the mechanization process and are called dynamic errors.

Many attempts had been made to minimize all errors types[1]. Static errors can be compensated by external calibration with another precision measurement system[2]. In this sense, laser tracker systems are used to calibrate the machine tool before the mechanization process. Dynamic errors are amplified by the improvement of speed and accelerations of both linear and rotational movements of the high-speed machines. These dynamic errors are already present at low speeds, but they are not so important. One can reduce the mechanized speed to avoid dynamic errors but then the processing time of the mechanized piece will be enhanced. The third class of errors, quasi-static errors, can be minimized taking into account numerical corrections of thermal expansion models and deformation models by performing forces depending on the materials involved in the process[1].

Since the development of the first He-Ne frequency stabilized laser, laser interferometers had been proposed for displacement measurement in the sub-micrometer region of resolution applied to the field of the machine tools and coordinate measuring machine. Today these techniques appear as very common systems in industrial successes[3] and a wide variety of methods can be applied to distance measurement and to coordinate determination. Photogrammetric measuring devices based on optical triangulation[4], laser trilateration[5], time-of-flight distance measurement[6], phase shift range finder[7], speckle tracking techniques for displacement measurement[8] and so on are some examples of techniques in constant development nowadays. However a great field of application of this techniques are involved with calibration procedures, error maps of machine tools and industrial robots, and alignment techniques, but not many of them are applied to continuous control in the mechanization process.

We propose a well-known measurement system (Michelson-Morley interferometer) integrated with a precise tracking system based in a estimation algorithm that are qualified together to real time machine tool control in high speed mechanized. Moreover, our measurement system removes most of the errors present in standard machine tools and reduces others due the complete measurement system is independent of the own machine tool measurement system and provides an estimation of one point closed to the drill machine tool. By the communication between the external measurement system and the machine tool controller, we can correct the on-line position of the drill and ensure an optimal precision in the pieces production. The main technical characteristics desired for the measuring system are 5 microns positioning precision, 1 m^3 minimum working volume, up to 2 m/s tracking capabilities, 4 kHz update and control frequency, and open interface to controller.

Section 2 gives a description of the optimized optical measurement system. In Section 3 we present a description of the tracking system with the estimation algorithm. Section 4 shows the specific designed machine tool with the implementation of the two previous described subsystems. In Section 5 we present initial results. And Section 6 presents some conclusions. A list of references concludes the paper.

2. OPTICAL SYSTEM DESCRIPTION

The optical measurement system is based in the interferometric Michelson-Morley principle (Fig. 1). A helium-neon laser source (1) with a long coherent length is used as light source having a 45-degrees polarized beam directed to a polarizing cube (3) with the help of a bending mirror (2). The polarizing cube splits the beam in two orthogonal polarized beams: the reflected beam in the reference arm with a vertical state of polarization, and the transmission beam in the measurement arm with a horizontal state of polarization. As it is known, a reflecting element for each arm is necessary in a Michelson-Morley interferometer. Our system uses a pair of retro-reflectors (5, 10) with vertex incidence to ensure the beam returning[9].

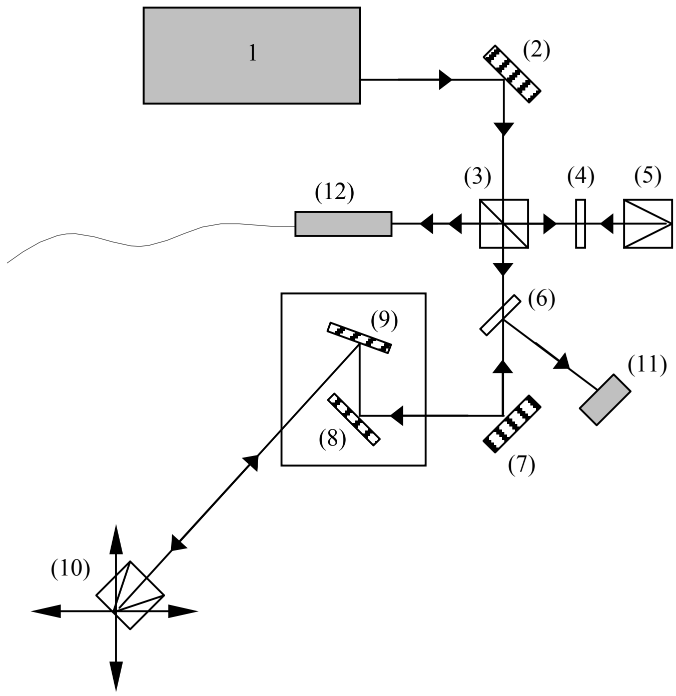

Fig. 1. Scheme of the optical components in the optical measurement system.

The reference arm (3-4-5) is needed to feed the interferometer detector (12) with a stable reference signal. The reflected beam in (3) is send to a static retro-reflector (5) after passing through a quarter wave plate (4) which transmission axis is oriented 45 degrees from the vertical. The static retro-reflector (5) returns the beam in the same direction towards the polarizing cube (3) and passing again through the quarter wave plate (4). As the quarter wave plate (4) is crossed twice in the reference arm, the polarizing state of the incoming beam in the polarizing cube is rotated 90 degrees and transmission in (3) is achieved.

The measurement arm (3-6-7-8-9-10) provides the capacity to measure the linear displacement along the beam axis. The transmission beam in (3) is send to a pair of galvanometric mirrors (8, 9) after single pass through another quarter wave plate (6). The galvanometric mirrors (8, 9) redirect the beam towards a retro-reflector attached to the mechanization head (10). This retro-reflector turns backwards the measurement beam that will travel along the same path with opposite direction, thus having a new incidence in the quarter wave plate (6). Then, the measurement beam reaches the polarizing cube (3) with a vertical polarization state. Due to the double pass through the quarter wave plate (6), a reflection is achieved on the polarization cube (3).

Both reference and measurement beams travel together from the polarizing cube (3) towards an interferometric counter (12) to evaluate the relative linear displacement of the mechanization head. In the Figure 2 we show an image of the entire optical measurement system. This linear displacement must be completed with the information of the tracking mirror system to obtain the position of the mechanization head.

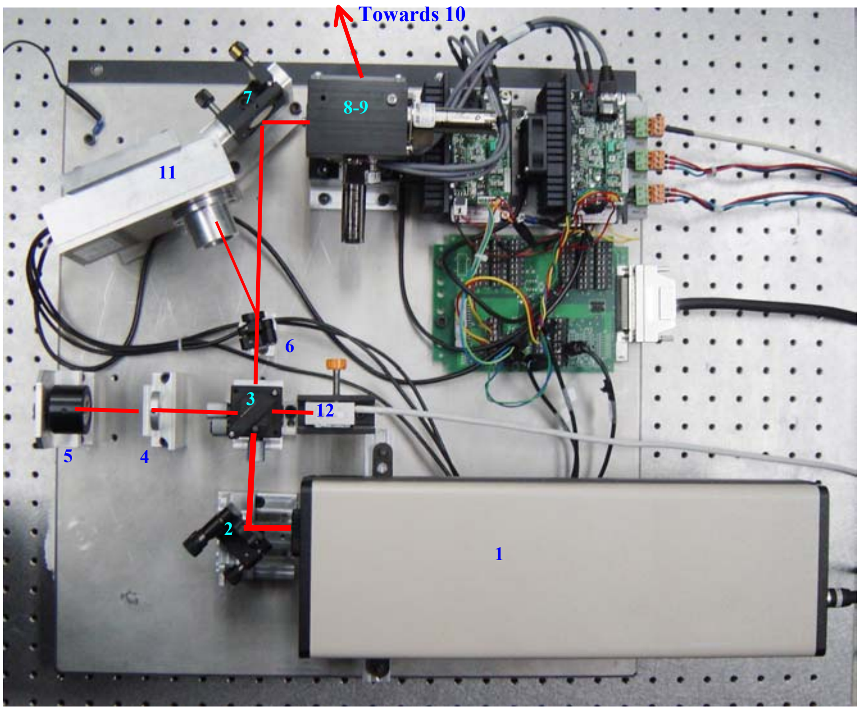

Fig. 2. An image of the different optical elements in the optical measurement system.

The interferometric fringe counter (12) must be able to register not only the movement but also to ensure the direction of the displacement to the retro-reflector (10) in the measurement arm. For this reason, the input incoming signal onto the receiver (10) is internally splitted into two identical signals because of the action of a intensity beam splitter. These two signals are used to obtain a pair of sinusoidal outputs with a phase shifting of 90 degrees between them due to the insertion of a quarter wave plate suitablely oriented in the travel path of one of them. Comparing the two signals in phase quadrature we are able to decide when the retro-reflector exhibits a change in its displacement direction. This is a critical aspect for a correct coordinate estimation of the measurement point.

3. TRACKING SYSTEM AND ESTIMATION ALGORITHM

The optical measurement system shown in Figure 2 must be connected with the laser tracking system in order to ensure the continuous overlapping of the two beams incoming from the two arms of the interferometer. Otherwise the continuous acquisition data with information about the linear displacement of the mechanization point is not possible. For this reason, to ensure that the incidence of the laser measurement beam hits in the retro-reflector vertex (10), the optical system includes a Positioning Sensitive Device, PSD, (11) that collect the incoming reflected light from the interface air-glass of the measurement arm quarter wave plate (6). During the initial calibration stage, the quarter wave plate (6) is oriented using a tilt-positioning mount, in order to achieve a perfect incidence at the centre of the PSD sensitive area meanwhile the beam hits the retro-reflector (10) at its vertex.

This tracking system uses linear range and pan and tilt angular data to provide the XYZ position of a retro-reflector (10) attached to the end-effector of the machine tool. As we already explained, range data is obtained from a laser interferometer. Angular movement, in order to continuously track retro-reflector movements, is achieved from a mirror-based beam steering mechanism using two independent mirrors commanded by two galvanometer motors (8-9). The system tracks the retro-reflector target by sensing the offset separation between the incident and the reflected beam using the positioning sensitive device, PSD (11). A general overview of the optical system with measurement and motion control stages is illustrated in Figure 3.

An offset *2e* (Fig. 3), between the incident and the reflected measurement beam, will be generated if the beam doesn't hit at the centre of the retro-reflector by an error *e*. At the PSD this alignment error can be measured, and therefore is used to redirect the mirrors and the beam to avoid that error increases in such a way that retro-reflector is lost. This offset error is referred to as the tracking error. The target position in space (X,Y,Z) is calculated by using the information retrieved from the interferometer, the PSD (tracking error) and the angular displacements (azimuth α and elevation β).

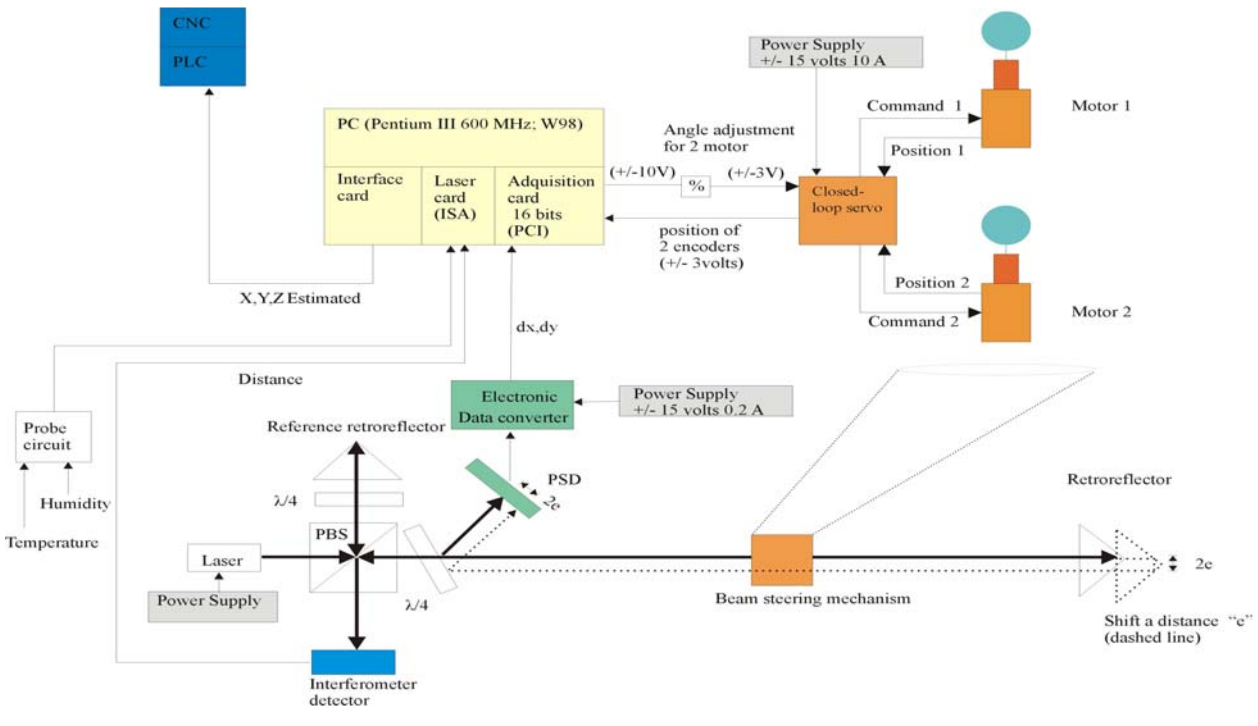

Figure 3: Layout of the optical 3D measuring system.

The retro-reflector position accuracy is guaranteed, apart from an initial calibration process, by a precise tracking and estimation algorithm. The purpose of the target-tracking controller is minimizing the tracking error *2e* (Fig. 3). The target tracking controller should be efficient and fast enough to follow the target and do not lose the track. The controller has to reduce this tracking error keeping the measurement beam as close as possible to the center of the PSD for two main reason. First, because of the PSD precision is higher at its center and second because we need the overlapping between measurement and reference beams to ensure the interference process.

The state of the art in target tracking methods and algorithms is wide, especially due to contributions coming from Radar research and Estimation theory. Some predictive control algorithms for tracking, use the information gathered in its present and previous states to estimate the future velocity and acceleration in Cartesian coordinates (X,Y,Z). Shirinzadeh and Teoh[10] proposes a controller that is based on Taylor series to calculate the future position, whereas Vinzce and Prenninger[11] minimizes a tracking-error cost function to estimate the future target position. Both algorithms present the disadvantage of being sensitive to noise. Kalman filter can be considered the optimum target tracking estimator and it is extensively used as the reference for object motion estimation[12]. It has the drawback of requiring significant computation time.

The target-tracking algorithm we present in this paper uses the angular displacement data of the motors and the PSD information to predict the future position and velocity (in polar coordinates) of the retro-reflector. The predicted position is used by the controller (PID) to minimize the tracking error. The controller generates the signals to activate the motors, reducing the tracking error. The layout of the predictive controller is illustrated in Figure 4.

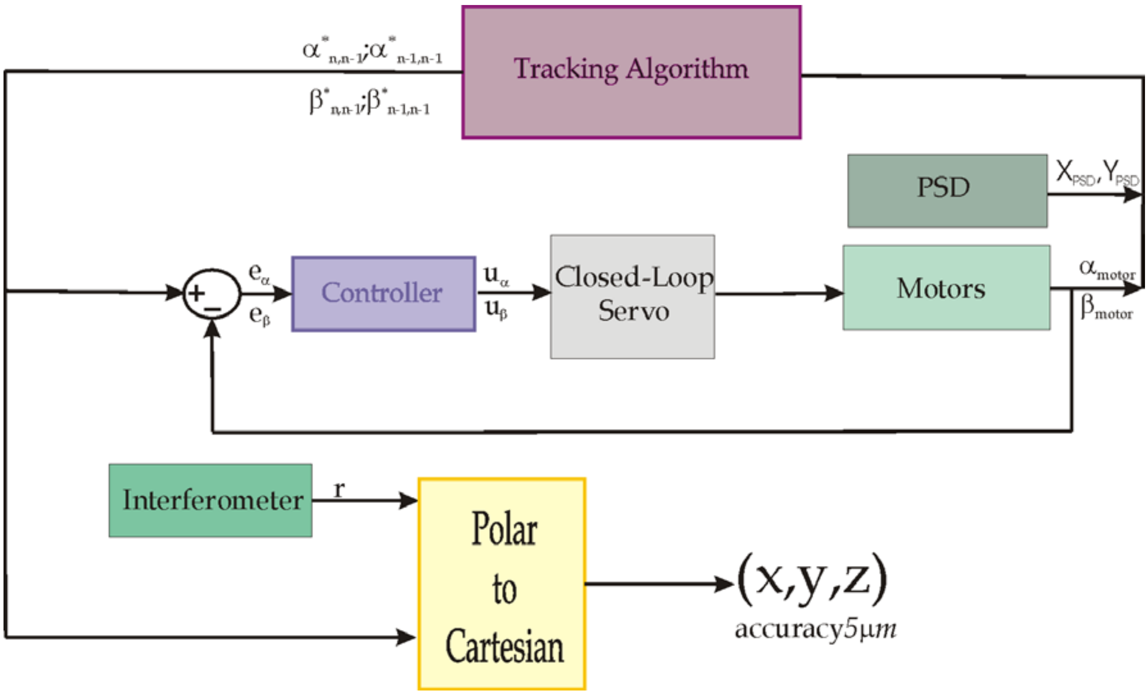

Figure 4. Layout of the Predictive Controller.

The tracking algorithm, which estimates the position of the retro-reflector, has to limit its maximum errors, between the real and estimated positions, to no more than 5 µm. Therefore, this algorithm has to average many samples in order to diminish the standard deviation of sensor readings and at the same time it has to allow quick transient responses at high speeds and accelerations (2 m/s and 2g). Both requirements compromise the selection of the size of the averaging window to be used, so the solution has to be found using higher updates rates and appropriated filtering techniques.

The g-h estimation algorithms used for estimating the position and velocity of the retro-reflector are given by the following equations:

$$\bar{x}^*_{n,n} = \bar{x}^*_{n,n-1} + h\left(\frac{x_n - x^*_{n,n-1}}{T}\right) \tag{1}$$

$$x^*_{n,n} = x^*_{n,n-1} + g\left(x_n - x^*_{n,n-1}\right) \tag{2}$$

$$\bar{x}^*_{n+1,n} = \bar{x}^*_{n,n} \tag{3}$$

$$x^*_{n+1,n} = x^*_{n,n} + T\,\bar{x}^*_{n,n} \tag{4}$$

The track update equations or estimation equations (Equations (1) and (2)) provide us the retro-reflector velocity and position ($\bar{x}^*_{n,n}, x^*_{n,n}$) at time nT after the measurement of the angular position of the motors (x_n) corrected by the information provided by the PSD sensor. The estimated position $x^*_{n,n}$ is based on the use of the actual measurement as well as the past prediction. The estimated state contain all the information we need about the past. As a consequence of filtering, the measured noise is reduced. This estimate differs from the prediction $x^*_{n+1,n}$ (Equations (3) and (4) called prediction equations) in which the latter is an estimate of x_{n+1} based on past states and prediction, and take into account the current measurement by means of updated states.

The selection of the g-h parameters depends of the dynamics of the target to be tracked[12] and the desired accuracy. The values obtained are $g=0.062$ and $h=0.002$, in order to achieve 5 microns accuracy for typical machine-tools trajectories. The position estimation update frequency is above 50 kHz. The control loop frequency, for commanding the motors to track the retro without losing it, is 2 kHz.

4. MACHINE TOOL DESIGN AND SYSTEMS INTEGRATION

A special machine tool was designed to allow the installation of the measurement system (Fig.5). This machine tool is a milling machine and has an empty platform of 0.5 m^2 to install the sensor at the rear of the working volume. It has been designed to allow laser steering over the working volume without laser beam interruption by any obstacle. For that reason, the design comprises gantry type architecture with a tool holding vertical ram. Other features of the machine are: a working volume of a cubic meter, 3 Cartesian axes, no degrees of freedom for tool orientation, digital drives for the motors of the axes and it uses a Fidia numerical controller. This numerical controller was selected due to its feature of allowing a direct connection of redundant position control signals, in addition to the connections at machine motor drives.

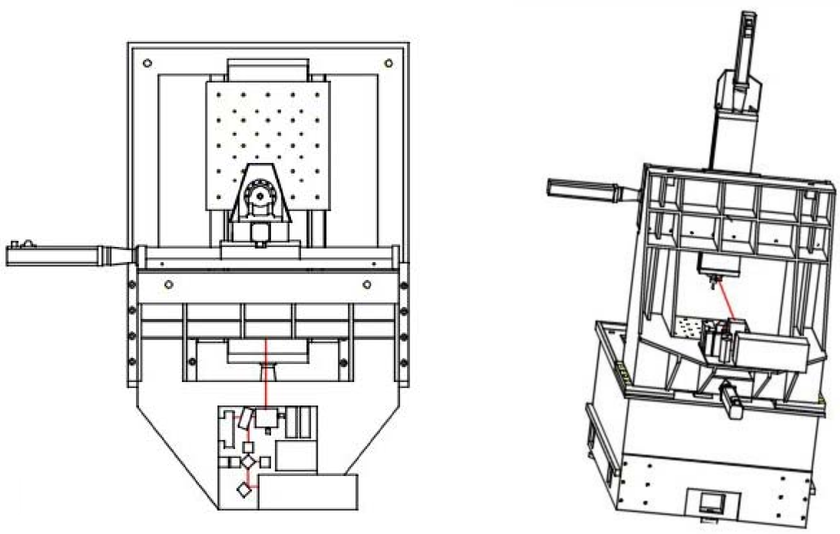

Figure 5. Especially designed machine tool with the measurement system.

A telescopic and flexible pipe has been installed from the retro-reflector to the mirror-based deflection device, to avoid laser beam interruption by chips or small particles coming from the milling process.

The measurement system incorporates an interface card and a pulse generation algorithm that transforms the XYZ coordinates into a sequence of quadrature pulses, emulating the signals generated by an encoder, for each of the three axes of the machine. These quadrature pulses provide the information needed for the position control, including forward and backward movements. The choice of generating this type of position signal resulted from the fact that most of the encoders and measuring systems for machine tools are able to generate this type of signal, which in turn is compatible with most of the machine controllers. These quadrature pulses, corresponding to incremental changes of position of the machine axes, are thus transmitted to the machine's numerical controller. This is the way the Fidia controller reads real-time information to perform tool control based on the sensor system presented in this paper.

In the following images we show some views of the machine tool with the integrated measurement system on its back position. With a dashed line we emphasize the measurement system and with a continuous line we remark the position of the measurement arm retro-reflector in the nearness of the mechanization point.

Figure 6. Two images of the machine tool with the measurement system accentuate by circle lines.

5. CALIBRATIONS AND INITIAL RESULTS

Until the calibration procedures are in a initial stage, some probes had been made. The machine tool has been calibrated using a ball-bar. Once calibrated, this machine was used as the reference to obtain the translation and rotation matrices relating the sensor and the machine tool coordinate references. Then, the machine is used to calibrate the optical measuring system. Tests have been performed comparing trajectories generated by the optical sensor and the machine controller, during the execution of typical predefined milling tasks.

Initial results shown a 15 microns coordinate estimation precision in a 0.5 m^3 working volume with 2 m/s maximum tracking velocity and with 3.3 kHz control frequency.

We are pendant to realize a more complex calibration, including standard pattern pieces manufacturing, to test the final capabilities of the complete mechanized system.

6. CONCLUSIONS

In this paper we had exposed a measurement system that enables on-line control in the mechanization process of a designed machine tool for this proposal. The measurement system is based in the integration and optimization of another subsystems. Thus, the Michelson-Morley interferometer configuration has been optimized to avoid beam power losses in the beam path through the optical components, the tracking system has been adapted to ensure measurement point continuous location by means of a pair of galvanometric mirrors commanded by a PSD, and the system measurement data had been integrated in the numerical control of the machine tool.

The benefits to be obtained with this measuring system in the high-speed machining area are wide. Most important sources of errors could be tackled and efficiently compensated due to the fact that the measurement system is external to the machine tool. In particular, gravitation, temperature effects, and most deformation and natural oscillations of the machine up to a frequency range of 50 Hz. From the production point of view, the advantages of an improved dynamic precision are a part quality improvement, a reduction of reject rate, and a cost reduction (saving of post finishing).

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