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Editorial

Special Issue on Manufacturing Metrology

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1. Introduction

Metrology is the science of measurement and can be divided into three overlapping activities: (1) the definition of units of measurement, (2) the realization of units of measurement, and (3) the traceability of measurement units. Manufacturing metrology originally referred to the measurement of components and inputs in a manufacturing process to ensure that they are within the required specifications. It also referred to measuring the performance of manufacturing equipment. This Special Issue presents a wide selection of papers on novel measurement methodologies and instrumentations for manufacturing metrology, from conventional industries to frontiers in advanced, hi-tech industries. Twenty-five papers are included in this Special Issue. These published papers can be categorized into four main groups, including length measurement, surface profile and form measurements, angle measurement, and laboratory systems. Detailed descriptions of these groups are introduced below.

2. Length Measurement

For the distance between two parallel surfaces, such as long gauge blocks, three methods are proposed. Using a combination of a laser interferometer and white light interference, the practical positioning method in end-plate surface distance measurement can achieve nanometer-scale precision [1]. Using a combination of laser triangulation sensors and a contact probe, not only the distance of two parallel surfaces but also the difference between surface shape contours can be measured to micrometer-scale accuracy [2]. With a multi-path laser interferometer, a new computational model for step gauge calibration was proposed based on synthesis technology [3], and a differential quadrature Fabry–Pérot interferometer was proposed separately [4]. In this measurement system, the nonlinearity error can be improved effectively and the DC offset during the measurement procedure can be eliminated. The turbine blade vibration was obtained by the blade tip timing (BTT) technique using the time of arrival (ToA) of the blade tip passing the casing mounted probes [5]. A fast laser adjustment-based laser triangulation displacement sensor was designed for dynamic measurement of a dispensing robot [6]. An invited paper contributed by Prof. S.W Kim's group from KAIST reported an absolute interferometer configured with a 1 GHz microwave source photonically synthesized from a fiber mode-locked laser with a 100 MHz pulse repetition rate [7]. This photonic microwave interferometer is expected to replace conventional incremental-type interferometers in diverse long-distance measurement applications, particularly for large machine axis control, precision geodetic surveying, and inter-satellite ranging in space.

3. Surface and Profile Measurement

On this topic, 12 papers were collected. A novel design for a surface topography measurement system was proposed in a relatively large area of 100 mm × 100 mm to

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achieve nanometer-scale accuracy [8]. The motion error of the stage was separated by a differential measurement configuration for a confocal sensor and a film interferometry module. The same group further designed an internal scanning mechanism for a confocal sensor [9]. By synchronizing the local scan, enabled by the internal actuator in the confocal sensor, and the global scans, enabled by external positioners, the developed system was able to perform noncontact line scans and area scans. Thus, this system was able to measure both surface roughness and surface uniformity. A non-scanning 3D imaging system with a single-pixel detector was reported to achieve 3D imaging of a target via compressed sensing to overcome the shortcomings of existing laser 3D imaging technology [10]. In order to solve the problems in the accuracy and adaptability of existing methods for blade twist measurement, a high-precision and form-free metrological method of blade twist based on the parameter evaluation of twist angular position and twist angle was proposed [11]. A rapid optical gear measurement system was developed for measuring the irregular tooth contours of large ring parts: the tooth root, tooth height, and tooth thickness of the workpiece [12]. The measured diameter was approximately 200 mm, and the radial inspection accuracy was within $\pm$20 μm. Compared with the conventional stylus contacting method, which takes a long time, this image processing method can be performed in one minute. An off-axis differential method for improvement of a femtosecond laser differential chromatic confocal probe was set up to obtain the normalized chromatic confocal output with a better signal-to-noise ratio. It achieved a *Z*-directional measurement range of approximately 46 μm as well as a measurement resolution of 20 nm [13]. For the purpose of in situ measurement, a design framework for optimizing spectral-domain low-coherence interferometric sensors was proposed for profilometry measurements to optimize system performance [14]. Another in situ measurement system dealing with the on-machine precision form truing of resin-bonded spherical diamond wheels was also proposed [15]. A novel nanotechnology presented a method for measuring the high-precision cutting edge radius of single point diamond tools using an atomic force microscope (AFM) and a reverse cutting edge artifact based on the edge reversal method [16]. For precision measurement of miniature internal structures with high aspect ratios, a spherical scattering electrical field probe (SSEP) was proposed based on charge signal detection. The developed SSEP has great potential to be the ideal solution for precision measurement of miniature internal structures with high aspect ratios [17]. For the evaluation of roundness of small cylinders, the linear-scan surface form stylus profilometer was employed. The technique used to compensate for the influences of measuring angular misalignments was also proposed, and the measurement uncertainty was analyzed [18].

Finally, in this category, the quality of wafer fabrication was studied in two papers. The first one was on the development of a dynamic pad monitoring system (DPMS) for measuring the surface topography of wafer polishing pads using a chromatic confocal sensor. It is applicable to monitoring the pad dressing process and CMP parameter evaluation to produce IC devices [19]. The second one used deep learning methods to develop a set of algorithms to detect wafer die particle defects from the captured images [20]. Both are practical in industrial applications.

4. Angle Measurements

Three papers on angle measurement technology were included. An innovative dual-axis precision level based on the light passing through a liquid container was designed and commercialized [21]. It works better than the current commercial levels as it is light weight, has a low cost, and has two axes for pitch and roll error measurement of machine tool stages. For the squareness measurement of five-axis machine tools, a technique using circular trajectories to identify the eccentricity and squareness error of the B and C axes was proposed [22]. Prof. Wei Gao's group from Tohoku University provided a review article on the optical angle sensor techniques based on the mode-locked femtosecond laser [23], which includes (1) the angle scale comb, which can be generated by combining the dispersive characteristic of a scale grating and the discretized modes in a mode-locked

femtosecond laser, and (2) mode-locked femtosecond laser autocollimators. This is so far the most cited paper in this Special Issue.

5. Laboratory Systems

Two papers were related to laboratory metrology systems. A GD&T-based benchmark for evaluating the performance of different CMM operators in computer-aided inspection (CAI) was proposed [24]. This, in turn, emphasized the importance of GD&T training and certification in order to ensure a uniform understanding among different operators, combined with a fully automated inspection code generator for GD&T purposes. Another paper dealt with the development of an enhanced circulating cooling water (CCW) machine [25]. It can simultaneously achieve high temperature stability and dynamic performance in CCW temperature control. The developed machine can satisfy the challenging requirements in precision manufacturing.

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