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3D Optical Measuring Technologies for Scientific and Industrial Applications

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Abstract:

Solving many actual safety problems in science, atomic, optics-mechanical and railway industry takes 3D optical measuring technologies with micro-/ nanometer resolution and productivity from 100 to 10^5 meas./s [1]. The novel results of the R & D activity of TDI SIE SB RAS in this field are presented.

Noncontact high-productive optical micro-/nanoprofilometer

The task for metallic surfaces local profile determination is urgent in many industries under the profile inspection of 3D produced details and especially their surface defects with micrometer-/ nanoresolution. TDI SIE have more then twelve years experience as for development and production the white-light profilometers.

The principle of object surface profile measurement is based on the interference phenomenon of partially-coherent (in time) light waves, emitted by polychromatic light source (e.g. filament lamp). Measuring device scheme based on Michelson interferometer is shown in Fig. 1, a [2].

For opaque objects as metallic ones the position and lateral configuration of interference area on CCD matrix is determined by intersection of reference surface and surface under measurement. This intersection determines the isoline, corresponding to the given depth along the axis *Z* in the direction of beam light incident on object. The registration of these areas by CCD camera allows to reconstruct this isoline (Fig. 1, b). To obtain 3D model of the inspected objects there is high precision scanning procedure in depth *Z* by the change of mutual location of surface under measurement and interferometer unit.

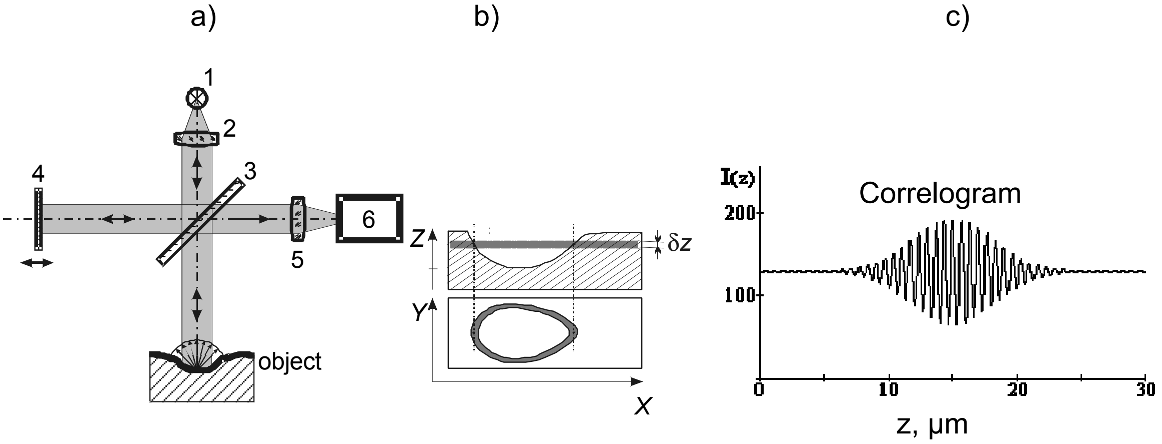
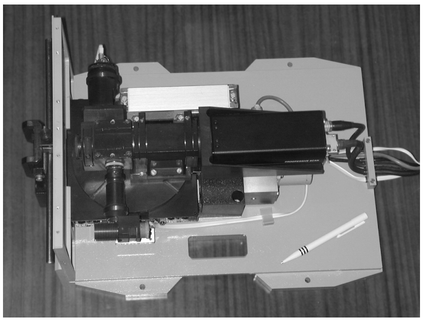


Fig. 1: Surface profile measurement principle by white-light interferometry: Michelson interferometer (a), isoline formation (b), correlogram for the coherence length ≈ 15 µm (c): 1 – white-light source, 2 – collimator, 3 – split mirror, 4 – reference arm mirror, 5 – objective, 6 – CCD camera.

We have developed and produced industrial version of the low-coherent profilometer PROFILE for 3D surface inspection (Fig. 2) within the range of 0,005 – 10 mm and resolution no less than 0,1 µm.

In 2010 TDI SIE have developed new type of measuring system – white-light microscope (Fig. 3) intended both for measurements of micro- and nanoprofile of surfaces by processing of correlograms (Fig. 1, c). In this case under scanning interferometer field with an interval few of nanometers correlogram is found from set of interference patterns for each point of nanosurface [3].



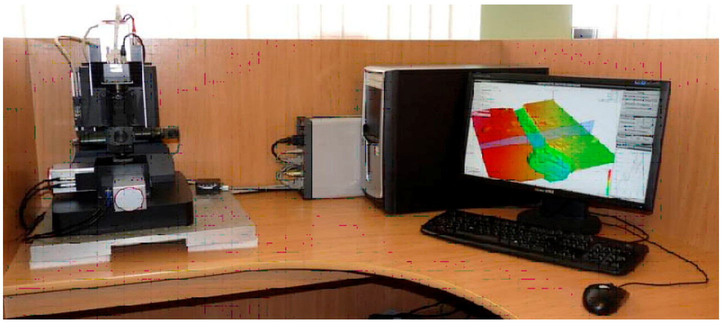


Fig. 2: Microprofilometer PROFILE. Fig. 3: White-light micro-/nanoprofilometer (microscope).

The correlogram maximum corresponding to a zero path-length difference of light waves scattered by adjacent surface parts in the reference and measuring arms of the interferometer determines the absolute axial position of the measured surface part [3]. The scanning range depends on the coherence length of the light source and can reach tens of microns.

Microscope operates in nano- and microregimes. Nanomeasurement regime is intended for measurement of surfaces relief height of surface finish class with resolution no less than 0,1 nm in the range of 0 – 50 µm. As for micromeasurement regime the microscope measures “rough” surfaces relief height with the performances the same as for PROFILE system.

Using in interferometer reference arm a perfectly (atomic-smooth) mirror (produced by “Nanostructures” Center of Semiconductor Physics Institute, SB RAS), as well as program-algorithmic software the breakthrough under measurement of relief height with resolution 20 picometers has been realized (Fig. 4). 3D-relief of stages (steps) with the height of 1 atom has been reconstructed. The results obtained are the base for metrological tasks solution in nanometer range as well as the creation of effective noncontact measuring devices with sub-atomic resolution on depth.

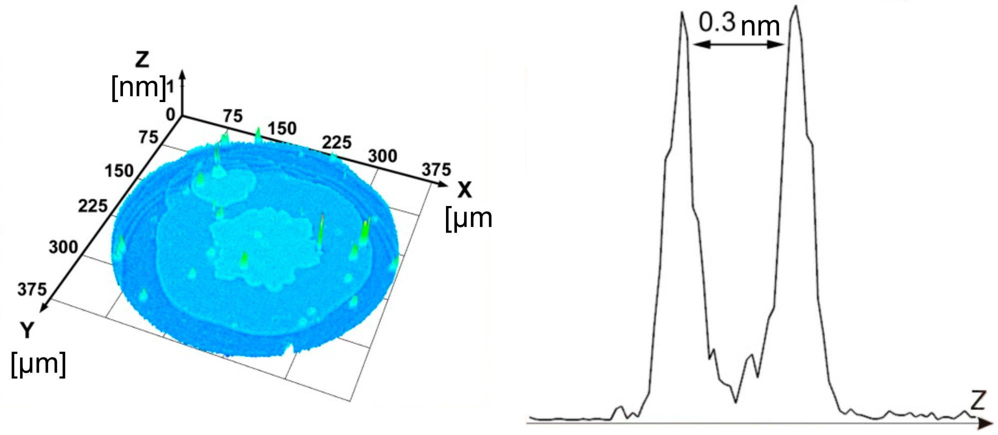


Fig. 4: 3D-relief and heights histogram of measuring one-atomic stages (steps) on surface Si crystal.

Application of these micro-/nanoprofilometers are very effective for science, including study of nanostructures and nanomaterials, measurement of film thickness, surface inspection of different polymers, micro crack detection and nanometrology.

The shadow mearsurements for 3D objects in partially coherent light

A shadow method is often used for inspection of 3D objects with clear shadow projections. For determination object's geometrical parameters the shadow images are processing by a threshold algorithm. The peculiarities of 3D object (thick edge) image formation in diffraction-limited system illuminated by a quasi-monochromatic extended light source have been investigated [4].

The optical scheme of the system to realize the shadow inspection method for 3D objects can be seen in Fig. 5, a. Extended source 1 with angular sizes $2\theta_s$ is illuminating 3D object 3 (thick edge with depth *d*) through objective of lens 2. Projection lenses 4 and 6 are forming its shadow image on photodetector matrix 7. The aperture diaphragm 5 with angular sizes $2\theta_{ap}$ is situated at focal distance from the lens 4. The typical image profile of the 3D object's edge can be seen in Fig. 5, b.

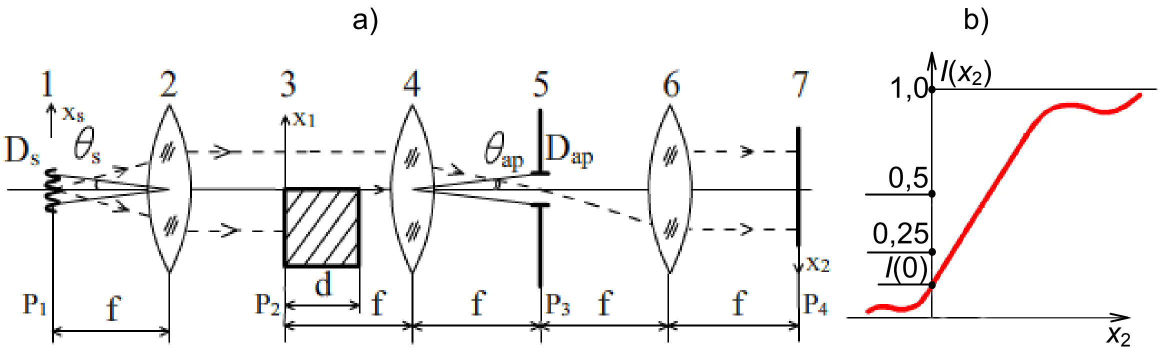


Fig. 5: Formation of 3D object's image in a diffraction-limited system: optical scheme (a); image profile of the 3D object's edge (b).

The value of threshold $I_{thr} = I(0)$ depends on many parameters, including angular size of the light source and the aperture diaphragm, as well as the object's volumetricity. In practice the threshold is equal to $0{,}25 \le I_{thr} \le 0{,}5$.

The influences of 3D object extension on the structure of the field in its image is determined by the ratio of critical diffraction angle $\theta_{cr} = \sqrt{\lambda/d}$ (under which the volume effects become significant) to the angular aperture size $2\theta_{ap}$ [5]. If at $\theta_{cr} >> \theta_{ap}$ the weak volume effects occur, so at $\theta_{cr} << \theta_{ap}$ their effects are sufficiently significant. For further calculations one has limited by weak volume effects taking place in practical applications.

An algorithm to determine the position of the geometric boundary of thick edge with inner plane perfectly absorption surfaces have been developed. It is based on the use of threshold $I_{thr} = I(0)$ (Fig. 5, b). For calculation we used the constructive theory of image formation for extended objects with sharp shadow projection [5]. One has shown that normalized light intensity in the thick edge image in point $x_2 = 0$ that coincides with 3D object boundary geometric position under $\theta_s << \theta_{ap}$ is equal to:

$$I_{thr} = I(0) = \frac{1}{4} + \frac{1}{3\pi^2}\frac{\theta_s^2}{\theta_{ap}^2} - \frac{\theta_{ap}}{\sqrt{2}\pi\theta_{cr}}.$$

At given parameters of d and θ_{ap} one has an opportunity, by choosing the angular source size $2\theta_s$, to compensate the effect of the object’s volumetricity on the change of light intensity at the point of geometric position of the thick edge boundary ($x_2 = 0$).

Computer modeling has allowed obtaining the dependency of the level of threshold on the angular source size (Fig. 6). According to the obtained results the threshold levels for the thick and flat edges illuminated by light source of different size are differed by the third component. Under $\theta_s = \theta_{ap}$ threshold level jump is observed. The theoretical results as well as computer modeling ones are in good agreement.

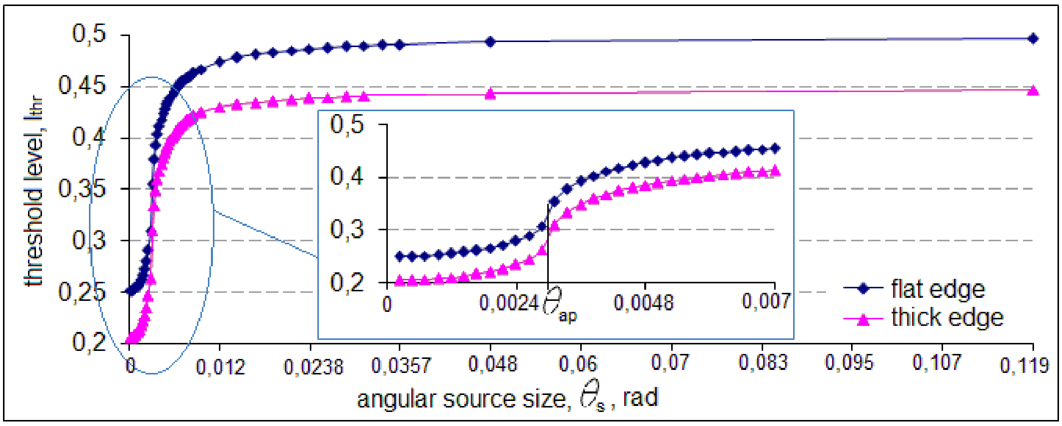


Fig. 6: The threshold level for shadow image vs. the angular source diameter.

The theoretical results obtained have been experimentally verified.

Universal laser measuring machine for atomic industry

Safety of nuclear reactors and ensuring their high exploitation reliability are urgent problem of nuclear mechanical engineering. It takes 100 % noncontact inspection of fuel assemblies, fuel elements, spacer grids and also fuel element surface inspection with micron resolution. To solve this problem we have developed and produced at TDI SIE some noncontact measuring technologies for Russian atomic plants, including 3D inspection of spacer grids and fuel elements for the fuel assemblies of nuclear reactors.

In 2009 year the universal structured light method for 3D inspection of Russian and western spacer grids using diffractive optical elements (DOE) has been developed by TDI SIE [6]. The DOE here is used as a part of the illuminator and focuses the laser radiation into a set of rings (Fig. 7).

The produced universal laser measuring machine (ULMM) (Fig. 8) allows to determine with some micron resolution the geometrical parameters of the spacer grid, which consists of more than 300 cells with diameter about 9 mm and in height 20 mm. The ULMM productivity is 15 min, which is three hundred times faster than existing universal contact coordinate measuring machines.

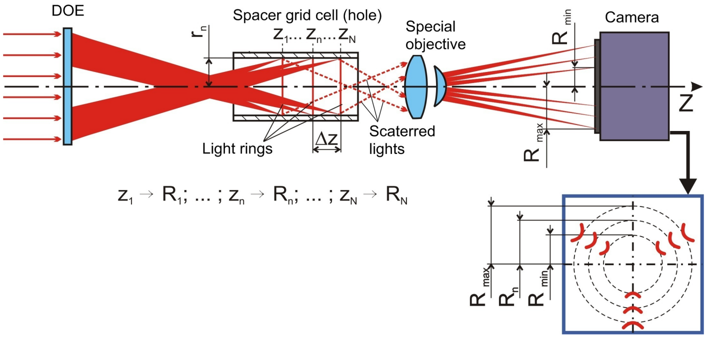


Fig. 7: The spacer grid cell inspection method using diffractive optical element.

Fig. 8: Laser measuring machine for spacer grids inspection.

The error for the diameter of the inscribed circle (the cell hole) has been less than 4 μm, the error for a cell's center positioning (the cell hole) is less than 12 μm.

The universal laser measuring machine is incorporated directly to the technological line fuel element manufacturing at the JSC NCCP (Novosibirsk).

Laser wheel pairs diagnostic inspection for running trains

Ensuring the safety of running trains is the actual task of railways exploitation and transport of passengers and cargoes all over the world. Regular inspection of wheels for detection of defects is the main task of movement safety, especially for high-speed trains. We have developed high-speed laser noncontact method for geometrical parameters inspection of moving 3D objects on the base of triangulation position sensors using fast-response PSD linear arrays (50 000 meas./s) [7].

Using this method (Fig. 9) TDI SIE has produced automatic laser diagnostic COMPLEX (Fig. 10) for noncontact inspection of geometric parameters of wheel pairs including: width and thickness of wheel rim; distance between inner sides of wheels; thickness of wheel flange; uniform rolling; wheel diameter; axle sliding-off. Measurements are fulfilled at freight cars speed up to 60 km/h. The range of working temperatures is from –50° C up to +50° C. At the present time about 60 systems COMPLEX are in operation on 14 Russian regional Railways (from Saint-Petersburg to Nakhodka, 9 000 km distance). Using these systems allows us to improve the safety of railway industry in Russia.

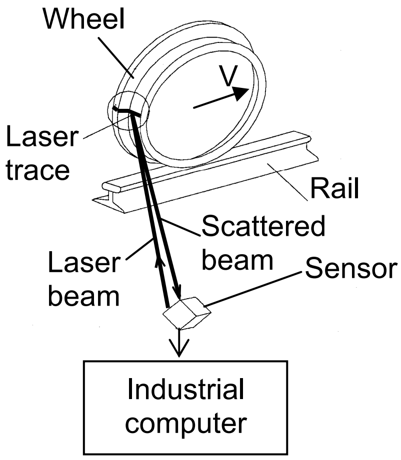


Fig. 9: The principle of self-scanning of running freight car wheels using triangulation measuring sensors.

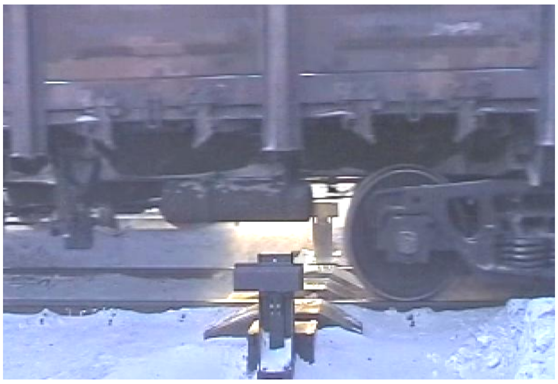


Fig. 10: Laser diagnostic system COMPLEX for wheel pairs inspection.

Automatic optoelectronic system for inspection of wire wear using high-speed image analysis

Safety of railroad transportation takes continuous inspection of the geometric parameters of wearing constructions, especially a contact wire wear and defects of a railroad network.

A structured light method and system testing results for noncontact inspection of wire wear and its defects for train electro-supply network were developed [8].

The optical layout of the measurement unit is displayed in Fig. 11. The pulse mode of the laser provides high brightness of the radiation scattered on the surface of the contact wire that has significantly increased the S/N ratio of the image. The small exposure time (from 5 to 20 µs) allows us to filter a significant part of background noise. Thus, the images obtained could be segmented into connected regions for subsequent processing. The images of unworn and worn wires, taken at frequencies of ~1000 Hz with structured light method, are displayed in Fig. 12.

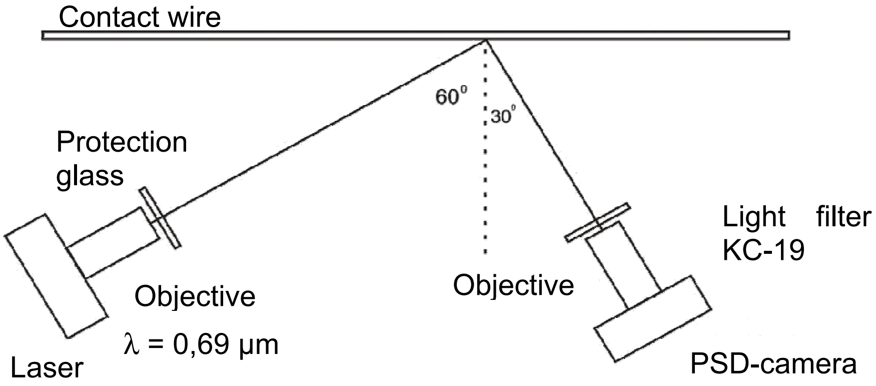


Fig. 11: Optical layout for contact wire wear inspection system.

Processing the curve, represented by the centers of mass detected one determines the profile of the contact wire cross section [8].

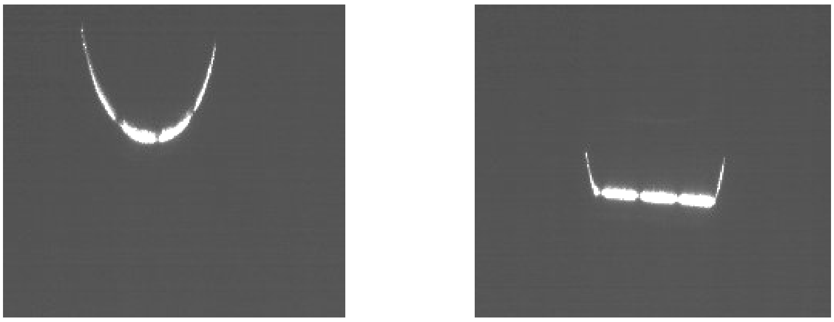


Fig. 12: Real nonprocessed image of contact wire under structured light for unworn wire (left) and worn wire (right) cases.

System has been tested on the «Seyatel» train station. Measurement system was fixed on the current collector of inspection vagon moving with 60 km per hour speed along a track section contains 2 contact wires in catenary suspension. The root-mean-square error for the measurements of the remaining height and contact pad constitutes 0.15 and 1.5 mm^2 correspondently.

High productive system for geometry inspection of large-size distributed objects

A measurement system designed for “on-line” high throughput simultaneous optical inspection of large set of geometrical parameters (more than 1000 points) defining geometry of some complex surface more than 10 m in diameter was created and produced. The measurement system is based on the distributed network of optical distance sensors. The system allows to measure up to 1700 linear distance parameters simultaneously in the range of 40 mm, with error 0.1 mm and sampling rate of at least 10^3 Hz.

The sensors are rigidly fixed in different places on a building berth, close to the measurement positions (points of interest). That makes sensors rigidly connected to the desired shape of the system which is to be replicated by the process. The data from sensors with the help of the specialized system of gathering of the information is transferred to a computer. The schematic diagram of such system is shown in Fig. 13.

We have developed compact optical triangulation sensor (Fig. 13, b) with measurement range ± 20 mm, error 0,1 mm, sampling rate 1000 meas./s, weight 40 g, overall dimensions 25 × 50 × 50 m [9].

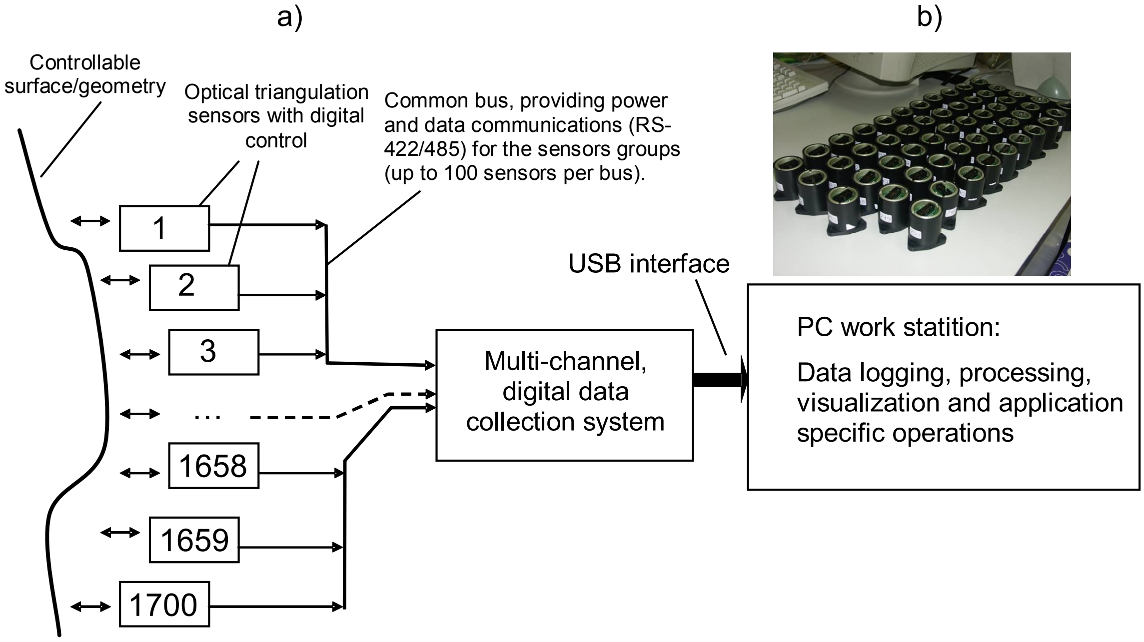


Fig. 13: Schematic diagram of the measurement system with sensors network (a). Sensors subset (b).

The system was manufactured and tested in real conditions. The developed systems can be applied in different industries: space, shipbuilding, aviation and so on.

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