4th International Congress
of Croatian Society of Mechanics
September, 18-20, 2003
Bizovac, Croatia

THE ASSESSMENT OF STRUCTURED LIGHT AND LASER SCANNING METHODS IN 3D SHAPE MEASUREMENTS

Stjepan Jecić, Nenad Drvar

Keywords: *3D scanning, structured light, laser, accuracy*

1. Introduction

The development of optical 3D shape measurement methods is rapidly gaining importance as industry raises its demands in high technical performance of final products, short production times, low manufacturing costs and the overall product quality. This development can be clearly witnessed by the vast number of research papers published in the last 20+ years [2] as well as by the number of commercially available measurement sensors [8]. During that time, not all efforts were engaged in the inventions of new measurement technologies, but were mostly dedicated to the refinement of the existing knowledge thus improving the measurement accuracy of the existing sensors.

Apart from scientific work dedicated to this field, further boost to the development pace was additionally given through the availability of cheap yet powerful desktop microcomputers, low cost CCD and recently CMOS sensors, cheap and eye-safe low power laser sources and various kinds of optical components. Clearly, both hardware and software components of the measurement sensors were improved over that period of time.

Typical example of free-form surfaces that respond to high esthetical, ergonomical and technical design is the automotive industry where product design changes on a daily basis. Since manual surface modeling requires a huge effort of time and money, this motivates further 3D optical shape measurement techniques development. This leads to many different specialized types of 3D scanners [8] that are developed in conjunction with the actual and often very specific industrial needs. However, not only industry motivates this development, as modern medicine, heritage, architecture and other end users recognize potentials of 3D sensors.

Nowadays, there are two mainstream non-contact optical measurement techniques that are well established with high technical and economic performance, based upon projected fringe and laser scanning methods.

In this paper, the assessment of the structured light and laser scanning methods in 3D shape measurements that are the core technologies of currently widespread 3D measuring sensors will be presented and critically observed. It will be done by analyzing basic principles of core technologies and potential sources of error of both mentioned methods, together with their current stage of application and achieved measurement accuracy on commercially available shape measuring sensors. Advantages and disadvantages with respect to various aspects are critically observed, like sensor types, method application, data acquisition conditions, measurement range, object reflectance, automation, accuracy, spatial resolution, method maturity, measurement planning and overall measurement costs.

2. Measurement principles overview

Based on the means that currently commercially available vision systems exploit in order to obtain object coordinates, vision systems can be classified as passive and active. Passive vision systems use the information contained in intensity coded images to obtain discrete object coordinates (e.g. classical photogrammetry), thus achieving high accuracy on well defined object/image features like coded targets or artificial and natural object texture and edges. Surfaces without those characteristic markings cannot be successfully measured with this type of sensors, which narrows its applicability so this type of sensors won't be analyzed here. Active vision systems however, obtain measurement information regardless of object visual features from the additional information provided by spatial and temporal active encoding, by utilizing structured light or laser beam projection techniques.

Both vision systems consist of similar optical components and thus have similar sources of error, but the influence of these sources doesn't affect the accuracy of the active and passive vision systems in the same way. I.e. in passive vision system image acquisition through optical lens system, features that define object surface and geometry, influence of ambient light and methods for feature detection can be regarded as functions of image coordinate measurements in 2D image field whilst sensor calibration provides required information for the location of the 3D object coordinates. In an active vision system however, sensor has the active role in definition of measurement point and its measurement range so the applied method for object point coding together with the sensor calibration and object features affects the accuracy and repeatability of location of 3D object coordinates with the active vision system.

However, regardless of the principle by which these systems obtain measurement information, both systems are still based on the ancient geometric triangulation principle for determination of the actual object point coordinates, which still provides high measurement accuracy. The only difference lies in the way in which the sufficient data for the triangulation procedure is obtained, e.g. single spot of a laser beam or a unique surface phase map produced via phase shifting.

Typical elementary active vision system usually consists of an active light source, a detection unit and a data processing unit. This leads to a conclusion that it can be expected that similar drawbacks affect both laser and structured light scanning methods.

Light sources used for measurement spot encoding emit either coherent light such as laser beams, or non-coherent structured light, or are a result of a third party production process such as plasma spot in the laser/plasma ablation process. Number and shape of light spots emitted by light sources can vary from a single point, line or a series of fringes. Therefore, the measurement speed, spatial resolution, accuracy and size of a single-view measurement volume greatly depend upon the chosen light projection method.

Modern detection units are often assembled of a rectangular array of photodiodes that are used for recording of spatial and temporal position of the light spot on the object surface. Regardless of sensor type, the influence of lens light distortion causes additional source of measurement error.

Data processing units are usually commercially available microcomputers capable of running both on-line and off-line analysis of optically gathered data. On-line processing might introduce latency in the time-dependent measurement techniques (e.g. time-of-scan laser triangulation or time-of-flight airborne earth scanning) or a complete loss of measurement data thus increasing the time and total cost of measurement process. A common mistake is the attitude that most of the known physical drawbacks of a scanning system can be solved via proper software routines, originated as a consequence of the specialization of research activities.

2.1 Laser scanner principle and error sources

Principles of laser scanner operation are sufficiently described throughout the literature [1,6,9], so here we'll provide just a brief description and put a focus on the sources of measurement error.

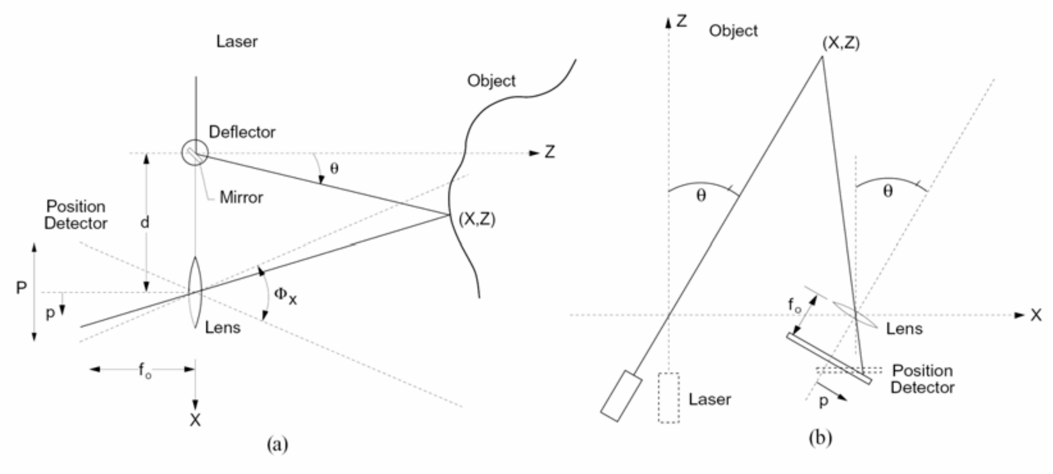

Figure 1.

Most of the laser scanner systems are based on the principle where one or more static detection units record projected coherent laser beam reflected off the object surface, *Fig. 1a*. Extension to this principle is the synchronized scanner approach *Fig. 1b*. where both laser and detector have a synchronous motion. Shape of the beam projected by modern sensors varies from a single spot, line (slit) or series of parallel lines, *Fig. 2*. Provided that the geometry of relative orientation of optical components (obtained by previous sensor calibration) is known, the object coordinates of the projected laser beam can be easily calculated by the application of triangulation techniques.

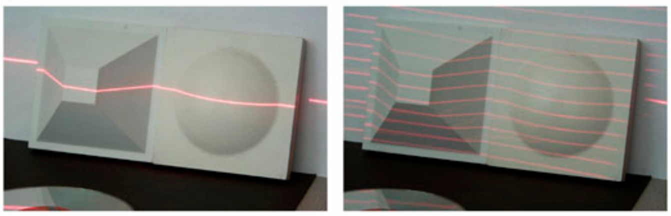

Figure 2.

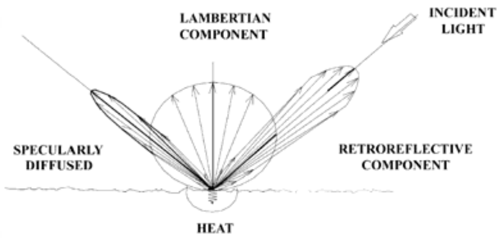

Figure 3.

Commercially available sensors utilize laser beams of different wavelengths, see *Table 1.*, with tendency of usage of low power outputs and eye safe wavelengths. If laser is used together with a CCD sensor, then wavelength of 670nm is suggested since it shows a good agreement with the maximum spectral sensitivity of the CCD sensor.

Manufacturer	3rdTech	Cyra Tech	MetricVision	Optech	Riegl USA
Laser wavelength (in nm)	670	532	1550	1540	904
Laser power (in mW)	5	1	4	10	1.2-85
Measurement range (in m)	0.3-12	1.5-50	0.3-55	1.5-1200	0.3-2500
Accuracy (mm at X m)	10 at 12	6 at 50	0.02	6 at 100	76 at 2400
Cost	$45,000	$125,000	$360,000	$150,000	$35-85,000

Table 1.

In general, the accuracy of calculated object points is affected by the errors introduced by the acquisition system geometry, reflectance of projected beam together with the ambient light changes, sharp corners and edges, sudden shape discontinuities with the respect to illumination, sensor occlusions, speckle noise and the inaccurate location of the projected line/point center.

Since shape measurements nowadays take place in many different illumination conditions, the use of spatially coherent, bright laser source is well justified. Obtained light is monochromatic, very directional and capable of staying in focus when projected on an object surface. But the speckle effect resulted by the projection of a spatially coherent light beam onto the optically rough surface introduces a shape variation of the spot image thus introducing error in point triangulation.

Speckles are a function of local surface micro topology, so the spatial triangulation analysis alone doesn't provide sufficient accuracy. Triangulation of points obtained by space-time analysis method [4] shows better accuracy, and is also capable of eliminating problems of a Gaussian point disappearance on the sharp object edges.

Spatial coherency is a feature of a projecting device so the only way of avoiding coherence noise is by altering object surface in such a way that the returned observed light spot shows incoherent properties or by using the incoherent light source. *Figure 4.* shows drastic effect of using non-coherent fluorescent light (right graph) versus measurement with the classical laser source (left graph) across a milled surface [7].

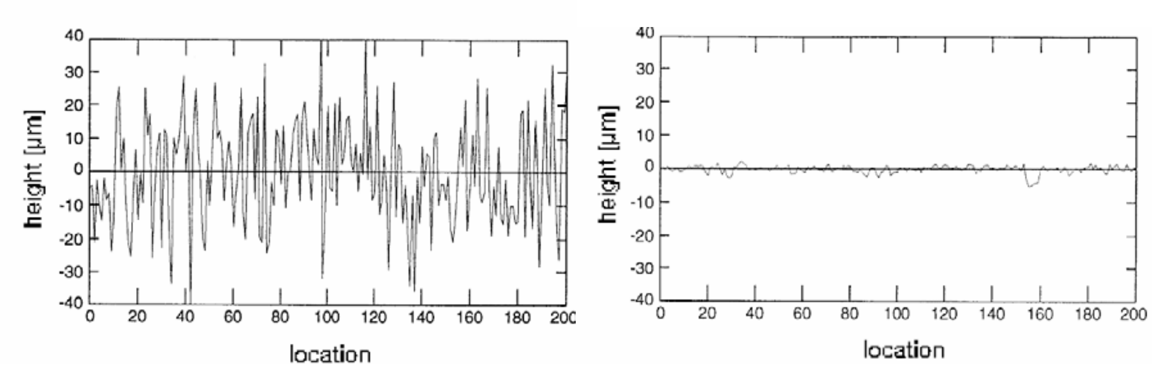

Figure 4.

Considering that triangulation assumes that the source of laser beam and the observation unit aren't coaxial, the backscattering from real opaque and diffusely reflecting surfaces has to be taken into consideration, *Fig 3.* Incident light falling on a real surface is distributed on the following components: retro reflective component, Lambertian component, heat and specularly diffused component. The weight of those components depends upon the surface properties. There are also materials such as marble (sculptures) whose structure allows light to scatter inside the material surface thus leading to the bias in distance measurement, and an increase in noise level.

If the surface of the measured object isn't specially treated to suit measurement needs, then it's also possible to obtain regions of high reflectance bordering with regions of low reflectance. *Figure 5.* shows the effect of the reflectance alteration on the position of true projected spot centroid and the actually measured centroid.

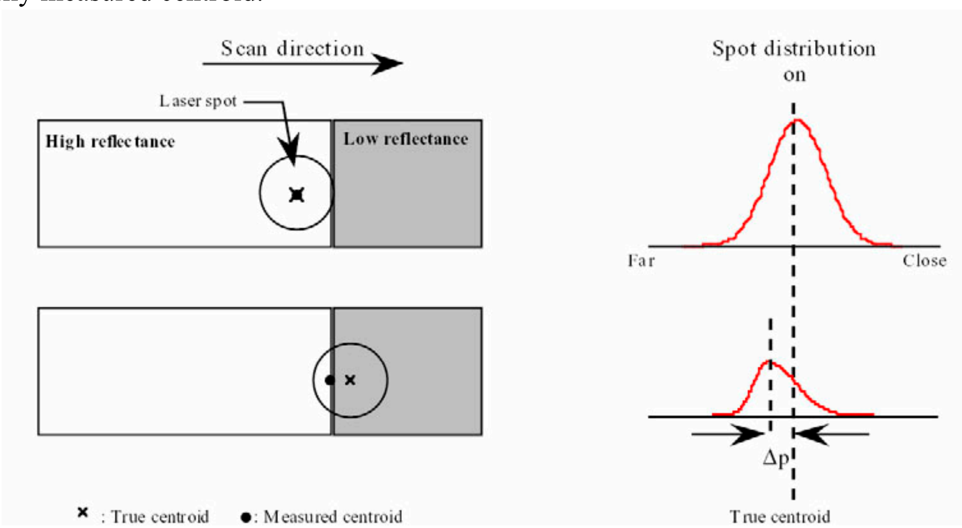

Figure 5.

2.2 Structured light scanner principle and error sources

Previous chapter outlines the effect of a spatially coherent laser source beam on the measurement point definition and thus on the triangulation accuracy. Structured light sensors, *Table 2.*, usually utilize visible non-coherent light sources for object point coding purposes that are projected on a whole camera field of view, thus being able to measure points in a range of a million within a single view measurement. Because of its non-coherent light source type, there is no speckle effect affecting the recorded images but its light intensity decreases rapidly with distance from the source.

Early types of sensors consisted of a single camera and single projecting device, *Fig. 6.* [10], but since the two cameras provide over-determined mathematical triangulation model [5], sensors with the two cameras of the same focal distances are nowadays more widespread. If there is a need for more than a single view measurement, unlike dual camera systems, single camera systems require a precise turn-table or the robotic positioning devices since they can't exploit the passive photogrammetric principles which require more than one observation of the same visually coded object spot. However, numerical registration of raw 3D points in different coordinate systems could replace the need of a precise mechanical alignment units providing there is a sufficient overlapping surface area with the distinctive features. Calculation of object point position is still based on the triangulation techniques, usually based on the principles of the epipolar geometry, *Fig 7*.

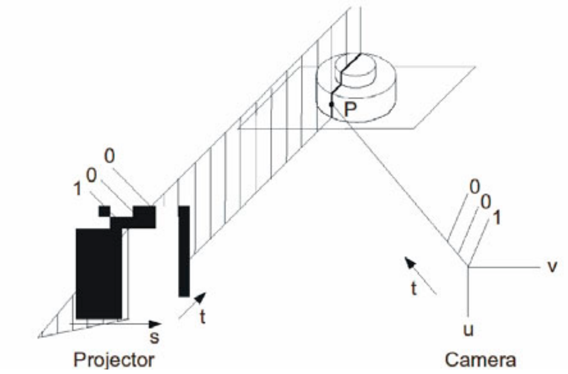

Figure 6.

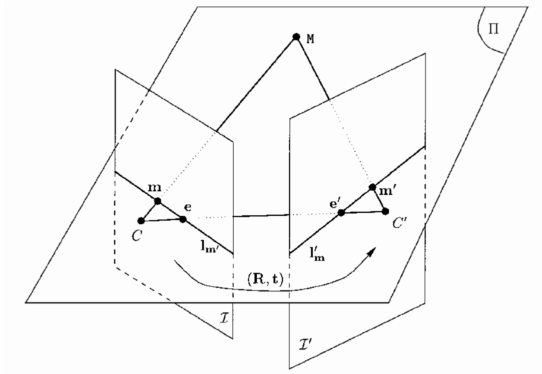

Figure 7.

During the measurements, the relative orientation between camera(s) and the projector is supposed to remain the same. This constraint is used as an assumption for a successful calibration of the sensor, i.e. determination of camera(s) intrinsic and extrinsic orientation parameters [5]. Taking into account finite camera sensor size and resolution, distance of the image plane from the object plane, the spatial resolution (number and spatial distance between measurement points in a single measurement) is a direct function of number of pixels in used cameras.

Fundamental problem with structured light projecting technology is in the correspondence problem, since to obtain triangulation points one needs to locate for each pixel in left image m the corresponding pixel in the right image m', *Fig 7*. Projector purpose is there just to provide the unique definition of matchable object points, hence for a dual camera system projector doesn't necessarily has to be calibrated.

The correspondence problem is being solved by projections of series of images consisting of some sort of structured pattern, *Fig 6.* [5]. The motivation is to obtain the unambiguous point (or stripe) indexing in all illumination conditions, regardless of the size of the measurement volume, object shape, surface color and reflection properties. Development of LCD projectors with the same or better resolution of cameras used, lead to systems based on projections of randomly distributed gray patterns, or even colored patterns [3].

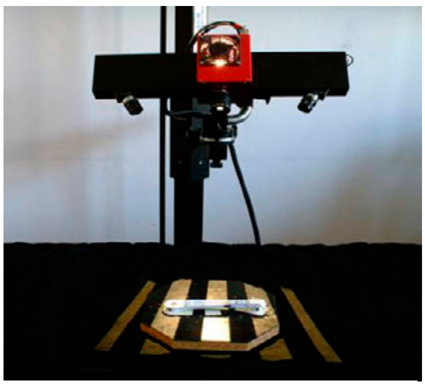
Figure 8.

Phase shifting methods, namely Gray code-based, *Figure 8.,* or heterodyne methods, are based on the multiple projections of various stripe patterns that provide continuous phase maps, thus solving the correspondence problem [5].

Ideally, measurement surfaces should be evenly illuminated opaque and bright Lambertian surfaces *Fig 9.* , but are usually dark or shiny with different coloring and unevenly illuminated as well as with the self-occluded areas.

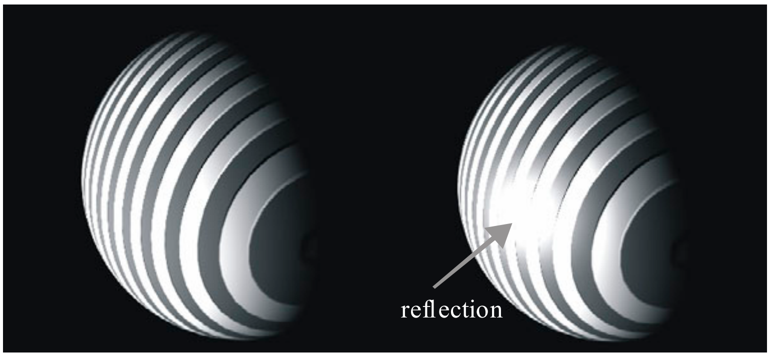

Figure 9.

To override possible sensor occlusions due to model geometry and curved surface reflections, current dual camera systems could be extended to operate as a combined system based on two single cameras and a calibrated projector device. Reflection on the flat surfaces can be easily reduced by a small change of sensor orientation, but curved surfaces always have areas whose normal coincides with at least one of the camera axis thus producing a bright spot regardless of the sensor orientation, *Fig 9.*

Table 2. presents some performance facts of several commercially available structured light sensors.

Manufacturer	Product	Accuracy [mm]	Measurement volume	Speed
GOM	Atos II	0.005-0.02	35x28x20mm to 1200x960x960mm	1,300,000 points in 7 seconds
Breuckmann GmbH	OptoTOP-HE100	0.015	80x60x50mm	1,300,000 points/second
Breuckmann GmbH	OptoTOP-HE600	0.050	480x380x300mm	1,300,000 points/second
Genex	EI 3D Digitizer	0.025-0.25	59x48x32mm to 250x200x200mm	442,368 in <1 second
Steinbichler Optotechnik	Comet C50	0.02	45x35mm	6666 points/second
Steinbichler Optotechnik	Comet C400	0.07	420x340mm	6666 points/second

Table 2.

3. Comparison

Evaluation of either method actual accuracy can be accomplished only by comparing it against the equivalent reference method whose accuracy, and possibly resolution, outstands the accuracy achievable by tested method. Previous chapters illustrated the influence of various parameters on their accuracy, so the presented methods thus won't be evaluated solely by their achievable accuracy, but rather by overall method maturity and their end application issues.

For a numerous applications the already achievable measurement accuracy satisfies their measurement needs, so the method maturity, degree of automation and overall cost of measurement, its planning time and learning curve should be a basis for decision of which system should one invest in. Facts in favor of previous statement show that it is often forgotten that measurement is just the initial part of the shape analyzing process, so it is also important to separately evaluate the quality of digitized data from the quality of measured point cloud. Meaning, not just which method is used for a specific measurement purpose, but in which ways it was used to obtain a complete model with all of its artifacts in a shortest time possible with the necessary point cloud density. To illustrate this statement, let us review a rudimental laser scanner as seen on *Figure 1*. The principle behind the active laser scanner consisting of a single camera and a projecting laser source allows it to acquire dense surface 3D information but from a single view only. If there is a need for a scan of a complete object's shape, then for the coverage of the whole measurement volume some sort of turntable or other means of a controlled mechanical sensor or object movement is required. This limits laser scanners usage to objects that are transportable and/or able to fit within sensor's measurement frame. However, such specialized scanners require less user influence than the other all-purpose scanners, thus minimizing scanning time and operator-introduced errors. Notice that the term measurement volume now has the extended meaning, in favor of a complete object's shape. Overall accuracy of such scanners will now depend not only upon the primary method drawbacks, but also on the accuracy of the point cloud alignment and registration.

Extension of the measurement methods to dual or more camera systems allows the integration of passive photogrammetric principles for the whole shape measurement. If the registration is conducted just with several photogrammetrically measured reference points then the possible error of the separate point cloud alignment might easily be bigger than the method's single view accuracy. The application of unique coded points to the object's surface requires certain time and experience but enables in-situ full-shape measurements of objects ranging even couple of square meters, something that laser sensors that are limited by their framed construction can't perform. In general, laser scanners usually (but not necessarily) are frame-based, and the structured light sensors can orientate separate measurements by additional optical measurements based on photogrammetry.

The accuracy of laser scanners slightly varies with the measurement distance, thus making it useful for various measurement tasks in several meter ranges, especially if there is a sudden change of illumination conditions. Structured light scanners of the similar accuracy are characterized with the smaller measurement volume, but in conjunction with photogrammetric measurements, this drawback can be reduced. Looking from the point of view of acquired data end user, measurement of large objects by structured light generates a huge amount of redundant data, which requires extra time for measurement, big storage space and is computationally costly during cloud alignment, registration and refinement procedures as well as during the post processing feature extraction. Because of the physical resolution of its cameras and mostly because of the significant influence of the ambient illumination laser scanner perform better than structured light scanners in case of large physical measurements.

Since projecting of various structured light patterns requires a certain period usually longer than a single second, laser method perform better in the real-time control measurements when there is a continuous and repeatable measurement task.

4. Conclusion

Which sensor type and measurement technique will be used for a specific measurement task one has to decide upon the characteristic requests for the post processing needs, taking into account the size of the measured object, required resolution, required accuracy, robustness, and acquisition time as well as the total cost of measurement. Both presented methods judging by commercially available sensors proved competitive and have achieved robustness and accuracy sometimes better than 0.01mm that is required for current industrial needs, but with regards to size of the measurement volume structured light methods are more suitable for smaller objects of irregular surface geometry while lasers can successively measure objects several meters in range.

If we extrapolate the preceding development pace, it becomes clear that the application of optical shape measurement will continue to expand. There is a general trend towards universal multi-sensor and multi-data measurement systems that will potentially result in a higher level of integration of those currently competitive techniques. Such integration would result in highly versatile systems that would widen its current application potential.

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Stjepan Jecić
Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb,Chair of Experimental Mechanics, pp 102, 10002 Zagreb, Croatia, Tel. 38516168105, E-mail: stjepan.jecic@fsb.hr

Nenad Drvar
Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb,Chair of Experimental Mechanics, pp 102, 10002 Zagreb, Croatia, Tel. 38516168447, E-mail: nenad.drvar@fsb.hr