Artur BERNAT
FINE MECHANICS DIVISION, MECHANICAL FACULTY OF ENGINEERING, TU OF KOSZALIN
Racławicka 15-17, 75-620 Koszalin

Mapping of the topography of abrasive tool cutting surfaces, with use of analyses of cast shadow distributions

Ph. D. Artur BERNAT

Artur BERNAT received his M.Sc. degree at TU of Gdańsk in 1993 in Electronics, and PhD degree at TU of Koszalin in 2010. The scope of interest of his PhD work was the machine vision and image data processing, adapted to estimation of stereometric parameters of cutting surfaces of abrasives. He is working on identification of changes of cutting surface of abrasives, in context of realization of grinding process, as well as, on identification of stereometric parameters of the machined surfaces.

e-mail: abernat@tu.koszalin.pl

Abstract

In this paper a method based on analyses of distributions of cast and attached shadows is presented. It is an alternative to the previously adopted Photometric Stereo method for superior task of mapping the topography of cutting surfaces of abrasives. In this method of geometric approach to the 3D reconstruction within regions of occurrence of the shadows, one spans descending height ramps with their inclinations and tilt angles in accordance to light rays,which are cast onto surface visually inspected.

Keywords: Photometric Stereo, vector gradient fields, 3D reconstruction from shadows, cutting surface of abrasive tools.

Odwzorowywanie topografii powierzchni czynnych narzędzi ściernych z wykorzystaniem analiz rozkładu cieni rzutowanych

Streszczenie

W artykule przedstawiono metodę rekonstrukcji powierzchni czynnej narzędzi ściernych. Wykorzystuje się w niej analizy rozkładu cieni na obrazach 2D intensywności. Opisano nowatorskie podejście do zagadnienia interpretacji rozkładu cieni rzutowanych, oraz częściowo cieni dołączanych, zawartych w obrazach 2D powierzchni. Obrazy 2D otrzymano w wyniku akwizycji danych, w etapie inspekcji wizualnej, dla ukośnie rzutowanych promieni światła. W metodzie tej, w miejscach występowania cieni generowane są zstępujące rampy wysokościowe, zgodne z kierunkiem promieni rzutowanego światła. Dane wysokościowe rozpinanych ramp miały na celu obrazować występowanie w topografii odwzorowywanej powierzchni zarówno uskoków wysokościowych, jak i zboczy nierówności, o dość znacznym nachyleniu. W pracy najpierw omówiono wady i zalety podejścia radiometrycznego i geometrycznego w odwzorowywaniu powierzchni narzędzi ściernych. W rozdziale drugim, przedstawiono sposób przetwarzania danych w podejściu geometrycznym, uwzględniającym zawartość wektorowych pól gradientu.. W rozdziale trzecim, omówiono sposób reprezentacji danych tych szczytów nierówności, które są permanentnie nieprzesłonięte. W rozdziale czwartym przedstawiono przykładowe wyniki rekonstrukcji 3D dla wybranego zbioru próbek narzędzi ściernych i powierzchni syntetycznych. W podsumowaniu określono możliwe kierunki rozwoju omawianej metody rekonstrukcji 3D.

Słowa kluczowe: metoda fotostereoskopii, wektorowe pole gradientu, rekonstrukcja 3D z cieni, powierzchnia czynna narzędzi ściernych.

1. Introduction

Nowadays, *in-situ* data collection in fully automated machining systems may provide extra information used for precise control of the processing parameters as well as maintaining the output product quality on high level. In case of grinding, among the set of unknown as well asuncontrollable input factors, there are those which are strictly correlated to the cutting properties of abrasive tools.

Cutting properties of abrasive tools, as they occur only during the machining process, may be expressed for instance in volumetric speed of the removing of material allowance destined to be ground off. Up to some degree, they depend on utilizable potential, which in turn indicates either good or bad performance of the grinding under strictly given conditions.

However, both of them, i.e. utilizable potential and cutting properties mostly depend on stereometric parameters of the abrasive tool cutting surface and they can be predicted during inference process, as well as subdued to prognosis process, respectively.

Therefore, what seems to be of utmost importance, in providing some additional information, regarding attaining of precise control of grinding process, is to realize *in-situ* data collection in relation to constantly changing during grinding topography of the abrasive tool cutting surface.

For instance, in previous works [1-4] the authors postulated the need of introducing visual inspection of the cutting surface of a grinding wheel mounted directly on the grinder within short spans of time (few minutes), between working cycles. In this methodology the data of a set of 2D intensity images acquired were used in 3D surface reconstruction process in radiometric approach.

With applications of various Photometric Stereo methods, the authors related results concerning the realization of 3D reconstruction process based on the set of 2D intensity images, which had been acquired for various samples of abrasive tools. In those reconstruction processes of the cutting surfaces of abrasive tools, just for avoiding excessive occurrence of inter-reflections, there was used an illumination set within light sources, oriented geometrically in such a way, as to obtain elevation angles for them in surface light illumination between 30 and 60 degrees.

While contributions of inter-reflections to intensity of the flux of light rays irradiated from the surface regarded can be only roughly approximated, these phenomena, as it seems, do not have to be taken into account due to binarized contents of the data, in form of a set of the acquired 2D intensity images. Elevation angles of light sources used in data acquisition, with subsequently realized analyses of distributions of the cast shadows, may be varied in more flexible manner.

Therefore in this paper, an alternative approach to radiometric ones is presented. That means, a method of 3D surface reconstruction, which was solely based on analyses of distributions of the cast shadows, is presented in opposition to radiometric methods, such as Photometric Stereo [4-8]. However, both approaches are embedded within context of multi-image visual inspection, with obliquely cast light rays into surface regarded.

2. Concepts of 3D reconstruction method based on analyses of cast shadows

There are generally two types of shadows occurring on the very textured surface with obliquely cast light rays. They are identified within contents of a set of 2D images as salient and distinct areas of lowered values of the resulted intensities.

First of them, the attached shadows occur when locally, directional parameter L of light rays of incident illumination of the surface observed is almost perpendicularly oriented, accordingly to N vector, normal to the surface. In this case, the resulted intensities occurring on the 2D images acquired in their digital representation seem to reach asymptotically the lowest value of intensities.

The second type of shadows, i.e. the cast shadows, usually occurs in the closest neighborhood of some irregularities of locally dominant character above the reference plane on the surface being observed. Thus, the second type of shadows occurs *quite naturally* and, moreover, must be somehow additionally implemented, when virtual illuminations of the surfaces are in question. In that case, each of the light sources is *a priori* assumed, as a distant one, therefore, as a light source, which is not immediately placed close to, or over each of the points on the surface observed.

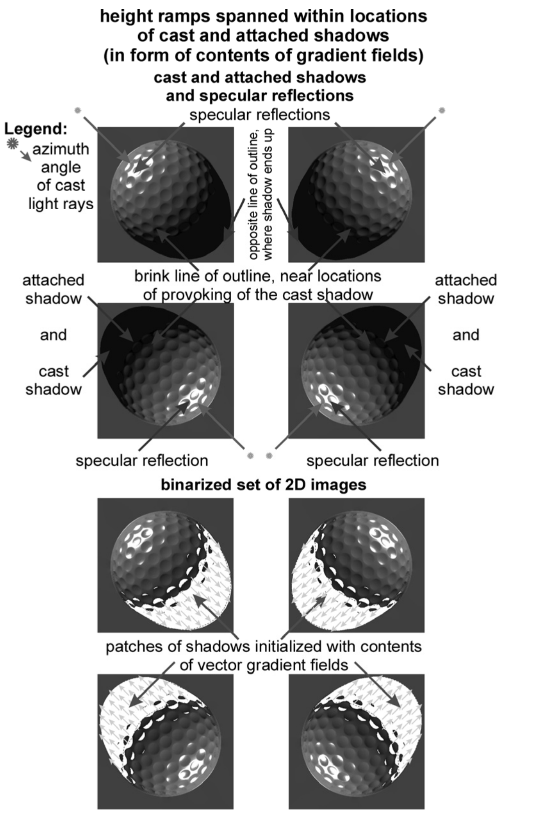

Fig. 1. Cast and attached shadows at binarisation stage of 2D images as well as spanning of height ramps in locations of their occurrence, with contents of vector gradient fields
Rys. 1. Cienie rzutowane i dołączane, na etapie binaryzacji obrazów 2D, jak również rozpinanie ramp wysokościowych w miejscu ich wystąpień, z pomocą zawartości wektorowych pól gradientu

The cast shadows, from their inherently acquired nature, as to mechanism of their occurrence, are these regions on 2D images acquired which are ultimately of the lowest possible values, within the set of data of the resulted intensities (see Fig. 1). Sometimes this phenomenon is even useful for observation or realization of inference process about the level of occurrence of inter-reflection phenomena or the level of presence of various types of noises and outliers, as well.

Noises and outliers are of subtle nature. Therefore, they cannot be easily observed elsewhere, except for the regions of occurrence of the cast shadows. Moreover, noises and outliers occur due to physical nature of components used in practical realization of data acquisition and processing systems. Therefore, the nature of the cast shadows, or more precisely: the regions of their occurrence, within data of 2D intensity images for textured surfaces, were objects of various and numerous analyses and studies, accounted within scientific community. Nonetheless, they are easily identified and extracted, with the simplest and trivial set of operators, at binarization stage.

In the method of analyses of distributions of the cast shadows, in practice, one actually assumed some arbitrarily chosen value of single thresholding operation. It stands in opposition to two-staged thresholding operations, used in initial classification of intensity data, as to assign them validity status in Photometric Stereo method, in radiometric approach.

However, this single value is usually set in such a manner as not to involve some phenomena of minor importance, such as noises, outliers and inter-reflections within intergrain spaces. And slightly elevated value of this thresholding operation in consequence partially allows contributing to form the aspect of the data process in next stages of the occurrence of attached shadows, conjointly with the proper occurrence of the cast shadows (see Fig. 2 for more finely presented contents of vector gradient fields).

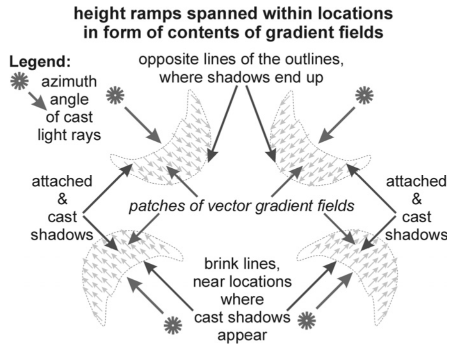

Fig. 2. Detailed view of contents of vector gradient fields
Rys. 2. Szczegółowy widok zawartości wektorowych pól gradientu

This in fact is not of such serious data misinterpretation so as to give excessively wrong results. The output results of the method of *3D reconstruction from shadows* have already proved, in numerously carried out trials and experiments, its validity. In other words, conjointly processed distributions of the cast shadows as well as partially taken into account the attached shadows with properly set slightly elevated thresholding value during binarization of 2D images prevent algorithm from taking into account noises, outliers and inter-reflections.

The general idea of the analyses of the shadows occurred is based on the assumption that cast shadows are mainly provoked by either occurrence of height steps or occurrence of slopes of irregularities of huge inclinations, in presence of obliquely cast light rays of incidence illumination of the surface observed.

Therefore, for each of the 2D images, which were properly binarized, the authors decided to *simulate* somehow the occurrence of both height steps and slopes of irregularities of relatively huge inclination with spanning height ramps. Of course, these are the descending height ramps, spanned alongside run light rays of incident illumination for each of the 2D intensity images. And they are spanned from some brink line in shadow outline – the possible locations of the summit or even the edge or ridge of the irregularity of locally dominant character which provoked overshadowing (mostly with occurrence of cast shadow), up to the opposite side of the shadow outline, where the cast shadow ends up.

These height ramps are spanned alongside the sense and azimuth direction of cast light rays, in accordance with elevation angles of the cast light rays for each of the light sources. And, analogously to use of methods of 3D reconstruction in radiometric approach, each of the light sources is activated singly and subsequently over the surface regarded, with a single step of the data acquisition realized at a time, giving in the result the number of 2D intensity images equal to the total number of directional light sources used in realization of the data acquisition stage.

On each of the binarized 2D maps these height ramps are initially represented with the contents of vector gradient fields. The module of the vector gradient field contents, placed exactly within the regions of the occurring shadows, is rather invariant for each location, and mostly depends on the elevation angle of the particularly used (activated) light source,

$$\sqrt{\left(p^2 + q^2\right)} = \left\|\{p, q\}\right\| \cong \cos(El), \tag{1}$$

where p and q are components of the homogenous vector gradient field within patches of shadows on each of the binarized 2D images, particularly considered.

Moreover, the direction and sense of contents of the gradient field depend mostly on the azimuth angle of the cast light rays.

$$p \cong \left\|\{p,q\}\right\| \cdot \cos(\pi + Az) = \cos(El) \cdot \cos(\pi + Az), \quad q \cong \left\|\{p,q\}\right\| \cdot \sin(\pi + Az) = \cos(El) \cdot \sin(\pi + Az) \tag{2}$$

Thus, each binarized 2D image, in the form of some logical map, was used in proper initialization of the distinct contents of vector gradient fields with rectangular outlines and the size equal to that of each 2D image.

In order to obtain the resulted 3D surface in this method, one has to sum up each of the respective contents of the vector gradient fields. The additive character of the vector gradient field contents, in that manner, allows for mimic (however, only up to some degree) the occurrence of both height steps and slopes of irregularities of huge inclination. So far, both of them have been bothersome topographic peculiarities in radiometric approach to the problem of 3D reconstruction for very textured surfaces.

Finally, the desired 3D surface, which is to be mapped in accordance with its topography and its topographic peculiarities as well, is obtained via numerical integration of the gradient field contents. This final step can be realized with use of either local, i.e. iterative, implementation of the Poisson solver or global implementations. And the last ones are some spectral closed-form formulas of solution for implementations of the Poisson solver.

3. Further elucidation of the 3D surface reconstruction method from shadows

The method of geometric approach to 3D surface reconstruction from shadows demonstrates also a set of obstacles and difficulties in its robust and reliable implementation.

First of all, it occurs most frequently that some of the summits of irregularities on the surface observed are permanently not-overshadowed from any directions of obliquely cast light rays. In that case, regions of locations on the 2D images acquired for these summits are void of any non-zero contents of vector gradient fields. Locations of patches of the vector gradient field do not reach in any case locations of permanently illuminated summits of some of the most distinct irregularities.

In other words, what is required in Photometric Stereo methods, which was previously used and adapted by the authors [1-4] as the methods of radiometric approach (that means permanent illumination of the summits from any given direction of incident illumination), actually in geometric approach becomes a serious disadvantage.

Thus, in consequence, due to the subsequently realized final stage of global numerical integration of the vector gradient field contents, these summits which are permanently illuminated are to be somehow *artificially* blunted. In the pursuit of an attainable and simultaneously reasonable robust and simple solution – the remedy for this inconvenience is taking into account a strong assumption. Namely, it is the assumption about umbilical nature of these summits which are totally not overshadowed (see Fig. 3).

Let us define an α quantity, i.e. a ratio of h height of the permanently illuminated umbilical summit of an irregularity to its radius r, at the base of a circle or most frequently an oval of the set of locations within the closest neighborhood of this irregularity which is also permanently illuminated:

$$\alpha = \frac{h}{r} = \frac{R-H}{r} = \frac{1-\sin\left(\frac{\pi}{2} - El\right)}{\cos\left(\frac{\pi}{2} - El\right)} = \frac{1-\cos(El)}{\sin(El)} = \tan\left(\frac{El}{2}\right). \tag{3}$$

In the relationship (3) presented R is the approximated radius of the umbilical sphere in modeling the permanently illuminated summit of the irregularity. Moreover, H is the height of that part of R, *i.e.* radius of the umbilical summit in its modeling which is permanently overshadowed. As it is shown in the relationship (3), one can actually infer about height h of the permanently illuminated summit of the irregularity in question, based solely on radius r, measured within the set of the binarized 2D images and concerning the circle or most frequently met the oval-like shaped regions of its corresponding, permanently illuminated closest neighborhood. And the quantity α in relationship (3), with tangent of half of the elevation angle of light rays of incident illumination of the surface observed is easily and robustly determined.

Let us assume that (x_c, y_c) are the pair of coordinates for the mass center of the particularly identified closest neighborhood of a distinct summit of the irregularity which is permanently illuminated. Likewise, let us assume, that (x_c, y_c) are the pair of coordinates of each of the currently processed locations within the closest neighborhood of the irregularity in question (Fig. 4).

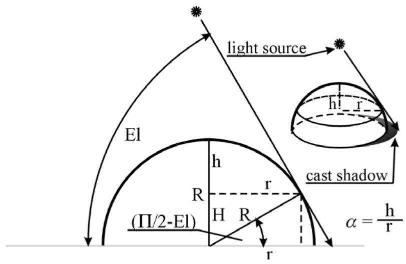

Fig. 3. Forming of the cast shadows and h value inferring based on measured r radius of permanently illuminated closest neighborhood of umbilical (in assumption) summit of the irregularity

Rys. 3. Formowanie się cieni rzutowanych oraz wnioskowanie, co do wartości h, na podstawie pomierzonego promienia r permanentnie oświetlonego najbliższego otoczenia kulistego (w założeniu) szczytu nierówności

Regarding these particularly considered locations within the set of binarized 2D images one had to adopt additionally implemented initialization procedures. The initialization concerned the module, sense and directions of the contents of vector gradient fields, which altogether are actually somehow different for each of distinct irregularities, permanently illuminated within set of 2D images.

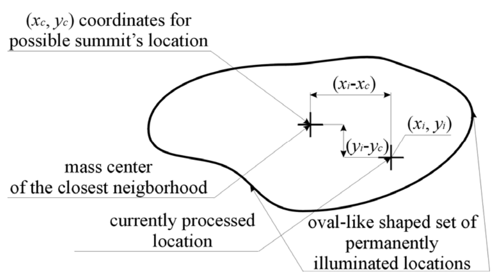

Fig. 4. Center mass and currently processed location in their coordinates, respectively, within the closest neighborhood of the irregularity summit

Rys. 4. Środek ciężkości oraz na bieżąco przetwarzana lokalizacja, odpowiednio co do ich współrzędnych, w najbliższym otoczeniu szczytu nierówności

In that case, one has to initialize the contents of vector gradient fields around each of such irregularities in such a way as to form some kind of slopes ascending towards these irregularities in questions:

$$p = -\tan\left(\frac{El}{2}\right) \cdot \frac{(x_i - x_c)}{\sqrt{(x_i - x_c)^2 + (y_i - y_c)^2}}, \quad q = -\tan\left(\frac{El}{2}\right) \cdot \frac{(y_i - y_c)}{\sqrt{(x_i - x_c)^2 + (y_i - y_c)^2}} \tag{4}$$

As it is shown in relationship (4), the initialized components of vector gradient fields within the closest neighborhoods of the permanently illuminated distinct summits of the irregularities need only the determination of relative distances between coordinates of center masses and currently processed locations.

4. Exemplary results of 3D reconstruction process for chosen set of surfaces virtually illuminated

Below there are presented skew aspects of the original and 3D reconstructed surfaces for both synthetic and real (abrasive tool sample) surfaces. With specific initialization of permanently illuminated locations on 2D images with contents of gradient fields, one should also take into account some mechanism of scaling for the heights of points on the 3D surface reconstructed.

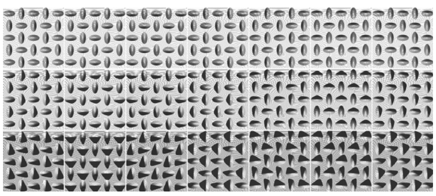

Fig. 5. Synthetic 3D surface with irregularities in form of distorted hyperboloids, in its virtual light illumination, with emulation of the cast shadows
Rys. 5. Syntetyczna powierzchnia 3D z nierównomiernościami w formie zniekształconej hiperboloidy, w jej wirtualnym oświetleniu z emulacją cieni rzutowanych

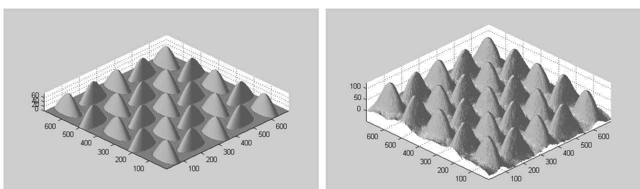

Fig. 6. Original and 3D reconstructed surface virtually illuminated
Rys. 6. Powierzchnia oryginalna i w rekonstrukcji (wcześniej wirtualnie oświetlona)

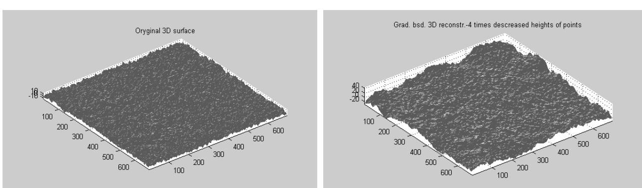

Fig. 7. Original and 3D reconstructed surface of lapping stone, made of silicon-carbide (descript. 99C120N) surface's sample of the abrasive measured with 3D profilometric tool), in its virtual illumination
Rys. 7. Powierzchnia oryginalna i w rekonstrukcji 3D osełki, wykonanej węglika krzemu (o ozn. 99C120), powierzchnia próbki narzędzia ściernego pomierzona z pomocą narzędzi profilometrycznych 3D, jej wirtualnym oświetleniu

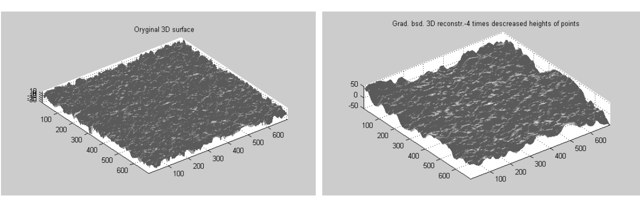

Fig. 8. Original and 3D reconstructed surface of section of grinding wheel made of silicon carbide (descript. 37C80, measured with 3D profilometric tool), in its virtual illumination
Rys. 8. Powierzchnia oryginalna i w rekonstrukcji 3D wycinka ściernicy wykonanej z węglika krzemu (o ozn. 37C80, przebadana profilometrycznie 3D), jej wirtualnym oświetleniu

Without such a mechanism introduced, there would be serious disparity between heights obtained due to cast shadows analyses, and heights for very summits, i.e. for the rest of locations. Therefore, it has been decided to present only some of the results, and without specific initialization in place of occurrence of permanently illuminated summits of irregularities.

5. Concluding remarks

The described geometrical approach to the problem of 3D reconstruction of cutting surfaces of abrasives proved its robustness and usefulness. In spite of the fact that it is biased with relatively low computational effort in relation to radiometric methods, it gave comparable results. Moreover, it is specially designed to cope with occurrence of both height steps and the slopes of irregularities of huge inclination. Both of them have been always bothersome peculiarities of the mapped topography for very much textured surfaces, in radiometric approach to 3D reconstruction problem. Nonetheless, the method needs some mechanism of setting correspondence between real and resulted height locations of points on the reconstructed surfaces. Therefore, it is postulated, to use in further evolvement of the method some iterative mechanism, possibly with the surface re-illumination mechanism. In that case, two distinct manners of initializing contents of gradient fields (i.e. for both shadows and locations of permanently illuminated summits) are to be integrated into single data processing framework. However, as it is shown in Fig. 5, this method needs a relatively huge set of the initially acquired, and then binarized 2D images. In the three exemplary output results (Figs. 6, 7 and 8, respectively), there were used some datasets, each of them consisted of 27 2D images of the resulted intensities. They are *acquired* with use of a virtually created illumination set. Such a virtual illumination set, in virtual illumination of 3 selected samples of surfaces, is built of 3 distinct subsets. Each set in turn consisted of 7 light sources, with elevations angles set to 24, 39, 54 degrees, respectively.

6. References

[1] Bernat A., Kacalak W.: Ocena cech stereometrycznych powierzchni narzędzi ściernych na podstawie danych zawartych w obrazach tych powierzchni, rozprawa doktorska, Wydział Mechaniczny, Politechnika Koszalińska, październik 2010r (PhD thesis).
[2] Bernat A., Kacalak W.: Problems In Derivation of Abrasive Tools Cutting Properties with Use of Computer Vision, Springer-Verlag Berlin Heidelberg 2007, 7nth Int. Conf. on Mechatronics, Warsaw 19-21 Sept. 2007.
[3] Bernat A., Kacalak W.: Problems of estimation of stereometric parameters of cutting surfaces of abrasive tools with use of Photometric Stereo, to be published in ATMiA.
[4] Bernat A., Kacalak W.: Estimation of stereometric parameters of cutting surfaces of abrasive tools in Photometric Stereo approach, with examples of samples of abrasive tools virtually illuminated, to be published in ATMiA.
[5] Smith M. L., Stamp R. J.: Automatic inspection of textured ceramic tiles, Computers in Industry, p.73-82, (43), 2000.
[6] Pernkopf F., O'Leary P.: Image acquisition techniques for automatic visual inspection of metallic surfaces, NDT&E International p.609-617, (36), 2003.
[7] Smith M.L., Smith G., Hill T.: Gradient space analysis of surface defects using a photometric stereo derived bum map, Image & VC p.321-332, (17), 1999.
[8] Woodham R. J.: Photometric methods for determining surface orientation from multiply images, Optical Engineering, (19),1, 1980.

otrzymano / received: 05.03.2012
przyjęto do druku / accepted: 02.04.2012 *artykuł recenzowany / revised paper*