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

Methodology of using the visual inspection and 3D reconstruction methods aimed at contactless diagnosing of abrasive tool wearing

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 the methodology used for contactless diagnosis of the types of abrasive tool cutting surface deterioration is presented in detail. It includes discussion of both realization of two-staged visual inspection of the cutting surface and newly postulated interpretation of data of the resulted intensities within the set of 2D images acquired. Moreover, important extensions of commonly known methods of radiometric approach to the task of 3D surface reconstruction, such as Photometric Stereo, are presented.

Keywords: contactless diagnosing, 3D surface reconstruction, cutting surface of abrasive tool, loading and wearing of grinding wheel.

Metodologia wykorzystania inspekcji wizualnej oraz metod rekonstrukcji 3D w bezstykowej diagnostyce zużycia narzędzia ściernego

Streszczenie

W artykule przedstawiono kompletną metodologię w bezstykowym podejściu do diagnostyki typów zużycia narzędzia ściernego. W rozdziale wstępnym omówiono mechanizmy tworzenia się określonych typów zużycia powierzchni czynnej narzędzia ściernego. W rozdziale drugim przedstawiono krótką charakterystykę właściwości odbicia światła powierzchni czynnej narzędzia ściernego. W rozdziale trzecim przedstawiono wady i zalety głównych metod w wielo-obrazowym podejściu do zagadnienia rekonstrukcji 3D powierzchni w jej obserwacji. W rozdziale czwartym przedstawiono nowo postulowaną interpretację danych wynikowych intensywności zbioru obrazów 2D, wraz z omówieniem nowego podejścia do inspekcji wizualnej powierzchni czynnej narzędzia ściernego. W rozdziale piątym podano szczegółowy przebieg analizy i przetwarzania danych z uwzględnieniem dwóch etapów inspekcji wizualnej, na przykładzie zbioru danych obrazów 2D wynikowych wartości chrominancji, dla powierzchni czynnej ściernicy wykonanej z korundu. W rozdziale szóstym krótko wskazano na możliwości zastosowania rozszerzeń znanych metod stereoskopii fotometrycznej. Natomiast w podsumowaniu określono stopień przydatności wskazanej metodologii w rozłącznej detekcji starć i zalepień powierzchni czynnej narzędzi ściernych.

Słowa kluczowe: bezstykowa diagnostyka, rekonstrukcja 3D powierzchni, powierzchnia czynna narzędzia ściernego, zalepienie i starcie ściernicy.

1. Introduction

So far known methods for contactless diagnosis of types of abrasive tool cutting surface deterioration could not tell the difference between the loaded and worn areas. Among them, there is for instance an advanced solution i.e.: a complete laser triangulation system for in-line measurements of grinding wheel perimeter topography during the machining process of ground materials. Moreover, the contouring of grinding wheel perimeter on a screen, placed behind the grinding wheel which is mounted directly on the grinder (in stream of collimated laser beam) is another interesting approach to the problem. For review of commonly known solutions see [1]. The worn areas do occur when summits of grains are worn down in direct or indirect contact with material of the machined surface. However, debris of the grinding process usually tends to load inter-grain spaces, thus leading to occurrence of the loaded areas on the cutting surface of abrasive tools.

In this paper the whole methodology of contactless approach to the problem is presented. Namely, two-staged visual inspection has been used with an illumination set, as well as a camera and the following system of the data processing, all of them placed near the grinding wheel, which in turn is mounted directly on the grinder.

Hence, it is methodology, which aims at realization of some *in-situ* data collection and instant data interpretation within short time spans (of few minutes), realized during for instance working cycles of the grinder, or in its idle mode when it is turned off.

Moreover, the data processing framework has been established with such relevant adaptations of commonly known 3D surface reconstruction methods so as to cope successfully with hard initial conditions, met during realization of data acquisition with use of both first and the second more general stage of visual inspection.

2. Light reflection properties of cutting surfaces of abrasive tools, briefly presented

First of all, cutting surfaces of abrasive tools are characterized by occurrence of phenomena of compound light reflections. Secondly, abrasive tools mostly are of very much textured surfaces. It is mainly due to randomly oriented abrasive grains and corresponding bridges of bond materials, which fasten them. In the first case, handicaps in mapping the surface with fidelity are due to the light reflection phenomena; there are conjoint occurrence of both matte and specular reflections, as well as of one of the most intricate phenomena, i.e. multiply inner light reflections in bond and abrasive materials of partial light transparency. In the second case, very much complicated topography itself of the cutting surface, with applications of light rays obliquely cast into the surface, tends altogether to provoke the occurrence of shadows. These are both attached and cast shadows occurring within the acquired set of 2D images of the resulted intensities.

However, it is very nature of topography of cutting surfaces of abrasive tools, which presents a serious handicap in its mapping with fidelity, in such radiometric approach to the 3D reconstruction problem, as for instance the use of Photometric Stereo methods (PS). In PS approach to the problem of 3D reconstruction of the textured surface, one here understands rather *quantitative* than qualitative mapping of its topography. The first one aims at point to point 3D surface reconstruction (including heights correspondences of points on surface). The second one would mean use of high-level recognition algorithms, for example for site locations of inter-grains valleys or grains summits.

3. General methods in task of mapping the topography of textured surfaces

PS methods actually are not real stereoscopic methods of 3D reconstructions. While stereoscopic methods adapt two or more points of observation, PS methods always use (in their classical core) a single point of observation, however with distinct variations in incidence light illumination. Thus, up to some degree, PS methods mimic results of 3D reconstructions, obtained with classical stereoscopic methods, which consider the variations of the scene from one to another point of view, however with constant or quasi constant conditions of incidence light illumination. In stereoscopic methods, it is the disparity between two or more points of view, which is the pivotal information in complex inference process of 3D reconstructions of the scene in its observation. In addition to that, very much textured surfaces still present themselves highly complicated task in 3D reconstruction process with classical stereoscopic approach.

As the scene, one understands here a complex set of background as well as foreground of a single or several objects, generally observed as motionless ones, with *constant* in classical stereoscopic ,or *variable* in PS light illumination conditions.

The important drawback of PS approach to the problem of 3D surface reconstruction is the need of application of an illumination set. It is designed with *a priori* known directional parameters of at least several light sources, activated singly and subsequently, with simultaneously realized steps of data acquisition of each of the 2D intensity images, respectively.

Another disadvantage of application of the PS method in case of a very much textured surface is impossibility of mapping its topography with fidelity, when height steps or slopes of irregularities of huge inclinations do occur. In that case, the author postulates the use of some geometrical approach conjointly with radiometric one, namely the 3D reconstruction method based on analyses of distributions of shadows. Such a method should be used in supporting locally the application of PS methods, or even in replacing radiometric approach to the task of 3D reconstruction methods, in case of much textured surfaces.

4. Extensions of the visual inspection and new data interpretation of the resulted intensities

Within compound light reflection phenomena, the most complicated are those, which are correlated to partial light transparency of materials of bonds and materials of abrasive grains. In work [1] the author postulated the need of introducing additionally realized actions. The abrasive tool cutting surface was to be covered with a thin opaque layer, thus canceling undesired multiply inner reflections in bond and abrasive materials. This serious alternation of light reflection properties of the cutting surface may be used as well in realization of a two-staged visual inspection. The first stage is to be realized before, while the second is to be realized after the covering of the cutting surface with the opaque layer.

Accordingly to the first stage of visual inspection, with subsequently realized data processing, it could be reliably carried out for these locations of the cutting surface areas which are generally of matte character of light reflections. In cases most frequently met in practice, these are some patches of occurrence of loading the inter-grains spaces with debris of grinding process. They are usually non-transparent and matte, however with some contributions of glossiness as well. And interpreting data of the resulted intensities from within the set of 2D images acquired, at this initially realized stage of visual inspection, might lead to a quite reliable 3D reconstruction process.

Nonetheless still, there is a problem with reliable 3D reconstructions of those other left areas, which are either worn i.e. with flattened summits of abrasive grains, or yet undeteriorated in any way i.e. the areas with relatively sharp summits which have not yet been blunted. However, after covering the cutting surface with the opaque layer, there is possibility of carrying out the extended data interpretation for the resulted intensities of 2D images, acquired in both first and second stage of visual inspection.

At this point of considerations, for the additionally introduced actions between two stages of the realized visual inspection, actually the opaque layer covers the whole rectangular aerial section of the cutting surface, i.e. area chosen to be observed and to be reconstructed due to the applied visual inspection. Therefore, all types of areas occurring on the abrasive tool cutting surface, both loaded and worn, as well as those areas which have not been yet deteriorated in any way (neither blunted nor loaded) are to be reliably reconstructed. In fact, the most intricate and complicated light reflection phenomena, due to partial light transparency of bond and abrasive materials, have been cancelled.

Accordingly to the dataset of 2D images, acquired at the first stage of visual inspection, the author postulated detection of loaded areas with analysis provided of the resulted chrominance values. For instance brownish patches of areas, loaded with debris of grinding process, are usually placed on the resulted 2D images against reddish or even white electro aloxite. Hence, there is rather a need for acquisition of the dataset of 2D images of the resulted chrominance values than the resulted intensities and subsequently provided 3D reconstruction process.

And the result of the detection carried out at the first stage of visual inspection produces a logical output bitmap. Namely, it is the *binary* output map which exclusively consists of both ones and zeros. This bitmap is obtained due to thresholding the distances calculated between the resulted chrominance values. That means the distance calculated between the values representing loaded areas (occurred on 2D images as brownish ones) and those representing other areas (for instance of reddish or white patches on 2D images). Within such a bitmap white areas indicate loaded areas, while black ones indicate other types of areas on the cutting surface.

Analogously, the results of the second stage of visual inspection and subsequently realized data processing must be also a logical bitmap. It is obtained with firstly provided 3D reconstruction process, and then with secondly provided detection of patches on the reconstructed surface, which are of relatively low inclinations of slopes of irregularities, or even which are equal to zero. From within the set of three possible states of the cutting surface, those regions which are not yet blunted present themselves a real challenge for applications of PS methods, due to much textured summits of abrasive grains. The problems of mapping the topography of undeteriorated areas on the cutting surface of abrasive tools with the fidelity have been discussed in [1].

However still, two other states of the cutting surface are to be also detected distinctly. Both loaded and worn areas can be detected, due to relatively low slopes of irregularities within them. As the output data in 3D reconstruction process is presented in PS implementations in a form of contents of the vector gradient field (see for example Fig. 6), it is the binarisation of its module values which produces an output logical bitmap.

The *notion* of contents of the 2D vector gradient field, derived at intermediate stage in PS, as well as some relationships governing the reconstruction process of 3D surfaces can be found in vast scientific accounts within Computer Vision literature. For the most basic concepts see [1-6]. It is sufficient to mention here that the contents of the gradient field represents the information about *slopes* of the reconstructed irregularities.

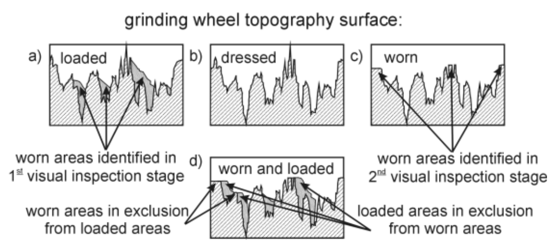

Fig. 1. Postulated data interpretation in disjoint and distinct detection of both loaded and worn areas of cutting surface of the tool

Rys. 1. Postulowana interpretacja danych w rozłącznej i rozróżnialnej detekcji zarówno zalepionych, jak i startych obszarów powierzchni czynnej narzędzia

Thus, the thresholding values imposed on the gradient field module, up to some degree, determine the roughness of the detected flattened areas. Subtracting the first logical bitmap derived in the first stage of visual inspection from the second one, actually one obtains distinct and disjoint information about both loaded and worn areas on the cutting surface of abrasive tools. And it is a *logic* subtraction operation provided for instance in the Matlab environment.

Yet another, analogously provided detection might avoid somehow troublesome, these additionally provided actions. It would be based on analysis of the shape and size, i.e. surface areas, of the generally considered worn areas in the first place and, moreover, of loaded areas in the second place, however of distinctly smaller sizes. Nonetheless, one could not be ascertained about the reliability of the would-be another approach to the problem, because some of the loaded areas of distinctly smaller sizes could be taken falsely for worn areas as well. Thus, resuming the currently considered matters, analysis of the module of the vector gradient field contents obtained by the PS method, is to be mostly used in detection of either bigger or smaller plateau with scantly occurrence of irregularities on it.

5. Exemplary results of disjoint identification of both loaded and worn areas on abrasive tool cutting surface

Below an example of the dataset of eight 2D images is presented. The dataset has been acquired from realization of the first stage of visual inspection for a deteriorated cutting surface of the grinding wheel. It is the data of the resulted chrominance values.

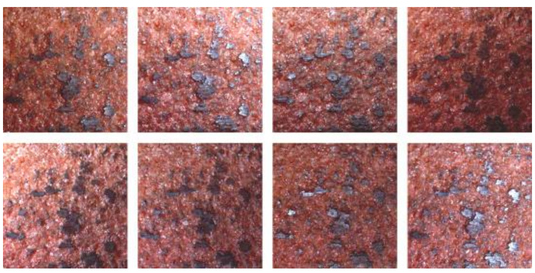

Fig. 2. The resulted chrominance values of the set of eight 2D images obtained from realization of the first stage of visual inspection
Rys. 2. Wynikowe wartości chrominancji zbioru ośmiu obrazów 2D w przestrzeni, otrzymanych w realizacji pierwszego etapu inspekcji wizualnej

As it is shown in Fig. 2 (these are images originally presented in chrominance), areas of the loaded cutting surface are clearly visible as black ones against reddish background of aloxite. Moreover, they are rather of matte light reflections, occurring within these locations, and could be easily reconstructed with use of many methods from within category of radiometric approach to the problem. However, other left areas are still characterized by partial light transparency, thus not to be told in difference between locations of either worn or sharp summits of abrasive grains.

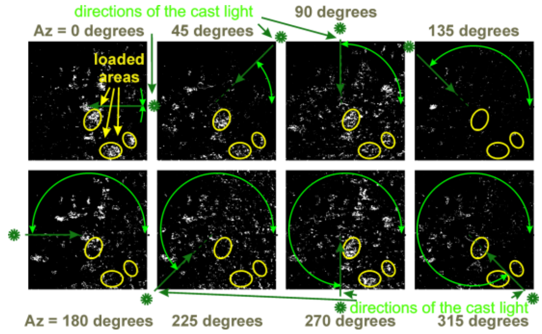

Fig. 3. Loaded areas detected, from realization of analysis of the data of the resulted chrominance values.
Rys. 3. Obszary zalepień poddane detekcji, w wyniku realizacji analizy danych wynikowych wartości chrominancji.

The set of eight binary 2D images shown in Fig. 3 has been obtained from some thresholding operations. Namely, the following thresholding operation has been realized:

$$ChrmnDist \le 12, \text{ for any locations } (x, y) \text{ on surface regarded}, \quad (1)$$

whereas, the thresholding value of 12 has been experimentally chosen.

The chrominance distance *ChrmDist* (considered here in the space of possible chrominance values, which preserves mathematically distance paradigms) is of the following definition:

$$ChrmDist = \sqrt{\left(R_{xy} - R_{L0}\right)^2 + \left(G_{xy} - G_{L0}\right)^2 + \left(B_{xy} - B_{L0}\right)^2}. \quad (2)$$

In relationship (2), for instance R_{xy} stands for in brief $R(x, y)$, i.e. R components, obtained for currently considered locations on the 2D image of the resulted chrominance values. In relationship (2), R_{LO}, G_{LO}, B_{LO} represent altogether some averaged values of the coordinates of points of representation of the loaded areas, occurring on 2D images, as well as, on the abrasive tool cutting surface:

$$loaded\_area = \begin{bmatrix} R_{L0} \\ G_{L0} \\ B_{L0} \end{bmatrix}, \quad (3)$$

as the unique correspondence has been implicitly assumed, of each of the points on discrete representation of the surface regarded to each of the locations on the 2D images acquired, respectively. Nonetheless, it is useful also to represent these three parameters $\{R_{LO}, G_{LO}, B_{LO}\}$ as values contained within the values of the following intervals:

$$lR_{L0} \in (114 - 116), G_{L0} \in (69 - 71), B_{L0} \in (56 - 58), \quad (2)$$

which have been experimentally determined.

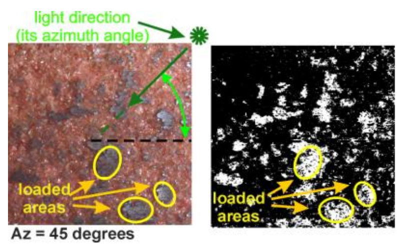

Fig. 4. On left: a single chrominance 2D image with obliquely cast light rays, on right: sum of all resulted logical bitmaps
Rys. 4. Po lewej: pojedynczy obraz 2D chrominancji z ukośnie rzutowanymi promieniami światła, po prawej: suma wszystkich wynikowych map logicznych

The contents of all the resulted logical bitmaps have been summed up to obtain much more reliable information from identification of the loaded areas, as variations of the irradiated light flux from the surface regarded at obliquely cast light rays might introduce ambiguity in detection.

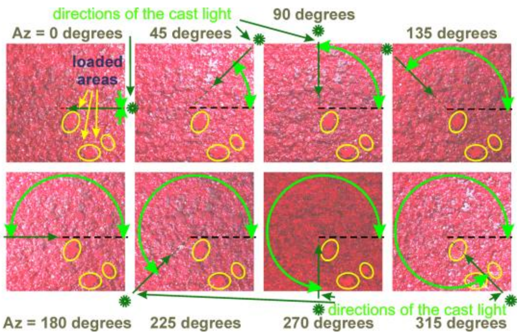

Fig. 5. Loaded areas in context of realization of the second stage of visual inspection
Rys. 5. Obszary zalepień w kontekście realizacji drugiego etapu inspekcji wizualnej

As it is shown in Fig. 5, covering of the selected aerial section of the abrasive tool cutting surface with the opaque layer allows performing the 3D reconstruction process, actually in relation to any locations within the 2D images acquired.

Moreover, the relevant side effect of these additionally introduced actions is a homogenous or quasi homogenous coefficient of light reflection, whereas at the first stage of visual inspection, no such assumption might be taken into account. In other words, in that case the value of the light reflection coefficient has been locally dependent. Mostly, it has been mainly dependent on light reflection properties of abrasive and bond materials (with the matte light reflection phenomena, considered in this paper, as the generally basic phenomena with analytical solution taken into account).

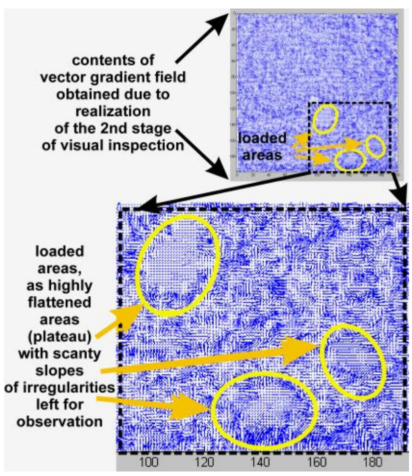

Fig. 6. Loaded areas, detected within contents of the obtained vector gradient field
Rys. 6. Obszary zalepień poddane detekcji w zawartości otrzymanego wektorowego pola gradientu

In Fig. 6 some of the identified plateaus of possible occurrence of loaded area are presented, these obtained with some specific thresholding operations, with analysis of the module of vector gradient fields. Quite analogously to the binarisation operation, provided with the first stage of visual inspection with relationships (1-3), there are some relationships used in this operations, however treated here, as a minor aspect of the problems and realization of the aimed task here related in this paper.

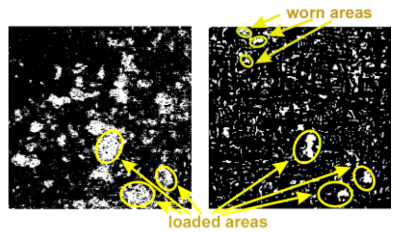

Fig. 7. On left: output logical map derived from the first stage of visual inspection, on right: the logical map derived from the second stage of visual inspection
Rys. 7. Po lewej: wyjściowa mapa logiczna otrzymana w pierwszym etapie inspekcji wizualnej, po prawej: mapa logiczna otrzymana w drugim etapie inspekcji wizualnej

As it is show in Fig. 7, sometimes worn areas occurring on the second logical bitmap do occur exclusively on the second logical bitmap. However, much more likely, some of the both loaded and worn areas might be correlated somehow, as to the locations of their conjoint occurrence.

Finally, with the realization of subtraction of the logical bitmap, that derived from the first stage of visual inspection, from the second logical bitmap, this derived from the second visual inspection, actually one obtains disjoint information regarding occurrence of both loaded and worn areas. Furthermore, the contents of the resulted logical bitmaps clearly indicates locations of occurrence of some patches of distantly smaller (on average) areas than those from the first and the second logical bitmap, respectively.

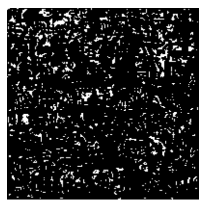

Fig. 8. The result of the subtraction of the first logical bitmap from the second
Rys. 8. Wynik odjęcia pierwszej mapy logicznej od drugiej map logicznej

That means the worn areas are saliently smaller in the areas of their occurrence, as the summits of abrasive grains usually individually interact with the machined surface, in these currently considered cases.

6. Introduced extensions of PS methods

The newly postulated methodology also includes new data interpretation of the resulted intensity, taken actually with the data of the closest neighborhood for each of the currently considered locations within the set of the 2D images acquired [1]. Moreover, at the final stage of numerical integration of the contents of the resulted gradient field, much more evolved closed-form solutions have been successfully used [1]. Both groups of extensions introduced into the framework of data processing, aimed at reducing considerably the impact of strong presence of noises as well as to some degree outliers during realization of 3D reconstruction process.

7. Concluding remarks

The paper describes both two-staged visual inspection and newly postulated data interpretation of the set of 2D images of the cutting surface as the innovative methodology for contactless diagnosing of abrasive tool wearing. The subsequently presented stages of data processing and interpretation as well as the exemplary presented output results proved its robustness. Therefore, it precedes so far known solutions as well as manners and algorithms for the data interpretation, allowing for constantly provided diagnosis of types of deterioration of the cutting surfaces of abrasive tools.

8. 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] Smith M. L., Stamp R. J.: Automatic inspection of textured ceramic tiles, Computers in Industry, p.73-82, (43), 2000.

[4] Pernkopf F., O'Leary P.: Image acquisition techniques for automatic visual inspection of metallic surfaces, NDT&E International p.609-617, (36), 2003.

[5] 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.

[6] 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*