

## APPLICATION OF 3D SCANNING TECHNIQUES FOR LARGE-SCALE OBJECTS MANUFACTURED ON CNC WELDING MACHINE

**Marek Grudziński, Krzysztof Okarma,  
Mirosław Pajor, Mateusz Teclaw**

### Summary

The modern CNC machines and applied advanced manufacturing technologies allow to enable fast accurate and elastic production, supporting the operator. At the same time the so called machine vision systems become more and more significant. Particular group of such devices, called 3D scanners, can achieve the accuracy of modern CNC machines and allow to control the quality of manufactured objects within less than one minute. In this research work a prototype of the vision scanning system for measuring the hole geometry is presented. The proposed optical device will be integrated with the IMCM machine, produced by Promotech company for large-scale objects welding. Reconstruction of the distorted edge will allow to correct the tool path for welding and edge beveling. A number of advanced procedures for image acquisition and processing, structured lights techniques, as well as 3D reconstruction have been developed and tested. Moreover, the calibration procedures for cameras with the help of coded markers have been proposed and simple interface for the operator has been created. Estimation of environmental factors, markers recognition and illuminating conditions for the final quality of reconstructed geometry required a series of complex experiments.

**Key words:** CNC machine, 3D scanner, structural light, geometry measurement, stereovision

### Zastosowanie technik skanowania 3D do wielkogabarytowych przedmiotów wytwarzanych na maszynach spawających CNC

#### Streszczenie

Nowoczesne rozwiązania mechatroniczne, stosowane do maszyn wytwórczych, w coraz większym stopniu wspomagają operatora i umożliwiają przyspieszenie produkcji. Jednocześnie coraz większe znaczenie odgrywają układy tzw. wizji maszynowej i różne rodzaje optycznych urządzeń pomiarowych. Skanery 3D osiągnęły dokładność umożliwiającą np. kontrolę jakości na maszynach CNC – czas pomiaru ich geometrii < 1 min. W pracy przedstawiono analizę wyników badań i prototypowe urządzenie optyczne do pomiaru geometrii otworów wycinanych w wielkogabarytowych konstrukcjach stalowych. Zaproponowany skaner 3D, zainstalowany na portalowej spawarce IMCM firmy Promotech, umożliwi szybkie skanowanie zniekształconych krawędzi i przekształcenie jej w trajektorię ruchu narzędzia spawającego. Zaprogramowano zaawansowane procedury przetwarzania obrazów, technik oświetlenia strukturalnego i rekonstrukcji 3D. Zaproponowano procedury kalibracji z użyciem markerów kodowanych oraz interfejs operatora z wizualizacją procesu pomiarowego. Wykonano eksperymenty

---

Address: Marek GRUDZIŃSKI, PhD Eng., Faculty of Mechanical Engineering and Mechatronics, Krzysztof OKARMA, DSc Eng., Faculty of Electrical Engineering, Mirosław PAJOR, DSc Eng., Faculty of Mechanical Engineering and Mechatronics, Mateusz TECLAW, MSc Eng., Faculty of Electrical Engineering, West Pomeranian University of Technology, Szczecin, e-mail: mgrudzinski@zut.edu.pl

mające na celu ocenę wpływu otoczenia, rodzaju oświetlenia i rozmiarów przestrzeni pomiarowej na dokładność odwzorowania geometrii.

**Słowa kluczowe:** maszyna CNC, skaner 3D, oświetlenie strukturalne, pomiary geometrii, stereowizja

## 1. Introduction

The modern CNC machines and applied advanced manufacturing technologies allow to enable fast accurate and elastic production. The machines are equipped with additional supporting systems for operator, which help to make right decisions and speed up the production. The industrial practice reveals that more than a half of the time is wasted for programming of the machine, positioning and fastening the workpiece and quality controlling. The operator has to mount the workpiece in proper position manually or by use of special measuring tools like touch-probe.

In modern mechatronic solutions the machine vision becomes more and more significant. The common term “machine vision” describes all techniques that accomplish various tasks based on images captured by cameras. Most of the industrial vision systems are used to increase the efficiency of production and to improve the quality control, reducing or eliminating the human factor. The most advanced systems with fast high-resolution cameras have been applied in serial production and highly efficient control of manufactured details, e.g. automotive parts [1].

One particular group of industrial and laboratory vision devices are those equipped with one or more integrated cameras and illuminators, allow to observe the workspace from different positions simultaneously. That means the stereoscopic spatial observations are possible. In special cases the illuminators are designed to project a series of light patterns, enabling 3D scanning of the object's geometry. These systems allow to create complex high-resolution 3D model and compare the geometry in reference to the CAD model [2].

At present there are no CNC machines integrated with 3D scanning systems, which allow to identify and position the workpiece in the workspace of the machine. This paper proposes a novel 3D vision system for efficiency improvement of the advanced welding IMCM machine, produced by Promotech company [3] from Białystok (Poland). Such machines are currently used inside wind turbine towers for large-scale cutting, beveling and welding in very specified position. With the help of 3D scanner the positioning of the machine in relation to the base coordinate system could be highly improved and correction of tool-path could be applied. The main issue is to determine the geometric relation between the camera's coordinate system and the IMCM machine's coordinate system in one space. Using the dedicated camera calibration procedures, pattern projection and software for image processing and markers detection, the complex 3D reconstruction of the welded object will be possible.

## 2. Illumination methods analysis

The lighting conditions during the scanning process are assumed to be strongly adverse, thus the measurement accuracy highly depends on the parameters of optical devices. Apart from the camera resolutions, a very important issue is the proper choice of the projection system for light patterns, characterized by intense, sharp and even illumination. The method based on the single laser fringe projection has been rejected because of long projection time and necessity for constant movement of machine axis causing camera vibrations.

Object reconstruction can be performed using only gray scale images, thus the best quality monochromatic fast cameras and single-colored LED light source can be used. Such a solution is commonly used in latest commercial 3D scanning systems, e.g. GOM Atos Core, Steinbichler Comet, Smarttech Micron3D, etc. However they all have limitations due to small measuring volume and narrow projection angle of about 30°. The application for the IMCM machine requires the specific light source with the projection angle of ca. 70° and possibility of full synchronization with cameras and control system. Moreover the compact solid construction and overheating resistance are highly recommended.

Previous investigations and experiences of 3D scanner producers revealed that the blue monochrome light (far from IR) provides the best efficiency for industrial applications. However, the most intensive illumination can be captured by cameras for the green light source, which is firmly advisable for adverse IMCM working conditions. Taking into account the above listed requirements and project assumptions, the compact light engine CEL5500 from DLI has been chosen. This projector has been further modified to work with 150W high-power Luminus LED.

## 3. Research stand construction

Since the objects welded on the IMCM are large scale, first experiment attempts have been conducted on full scale wooden model of a single segment of the wind turbine tower. Also the IMCM model was constructed, including a movable X-axis beam, carrying two cameras and a projector. Two different versions of the segment models have been created simulating the segment before and after cutting the hole for a jamb (Fig. 1). This research stand has only been created for experimental tests for multi-step 3D geometry scanning within the long object, with the help of additional magnetic markers. On this stage it is not necessary to move the machine axis precisely in relation to machine coordinate system. Only the calibration procedures for extrinsic camera parameters have to be performed.



Fig. 1. Research stand and different models of steel plate with excised hole and edge simulation

#### 4. Software

The first experimental scanning system has not been required to operate in real-time and has been developed in Matlab environment with additional image processing and acquisition toolboxes. The great advantages of Matlab are possibilities of rapid code development and testing, considering well programming experiences of the authors. In the next step all procedures have been translated into C-code and implemented in Visual Studio environment, including OpenCV and OpenGL freeware libraries. The system operations have been designed as multithreaded, thus the real-time image analysis and 3D measurement of marks have been enabled. Moreover, a simple interface for the IMCM operator has been designed, including real-time camera preview and markers detection, to visualize the 3D measurement results and to support operator's decisions.

#### 5. Calibration of camera parameters

The most commonly used model for camera calibration, called pinhole model, is based on perspective projection technique. According to Fig. 2 and equation (1)÷(3) the projection model includes the so called *intrinsic parameters* i.e. focal length  $\alpha$   $\beta$ , cross point  $(u_0, v_0)$  of main optical axes and CCD, sensor skewness  $\gamma$ , and so called *extrinsic parameters*, i.e. orthogonal rotation matrix  $R_c$  and translation vector  $T_c$  in relation to the world coordinate system  $W$ , associated with calibration pattern.

Point transformations from the 3D space to image sensor can be described with so called homography matrix (Fig. 3), including both types of camera parameters. During camera calibration a reverse task is performed, resulting in the new homography based on known 3D points  $p$  in  $W$  space and their projections  $p'$

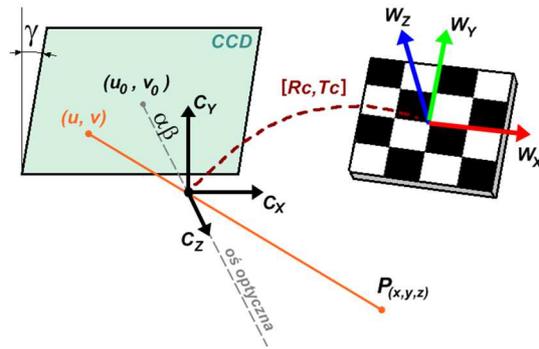


Fig. 2. Camera model explanation

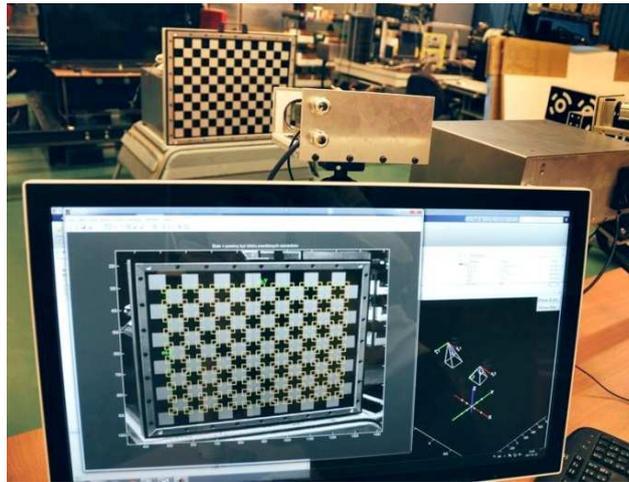
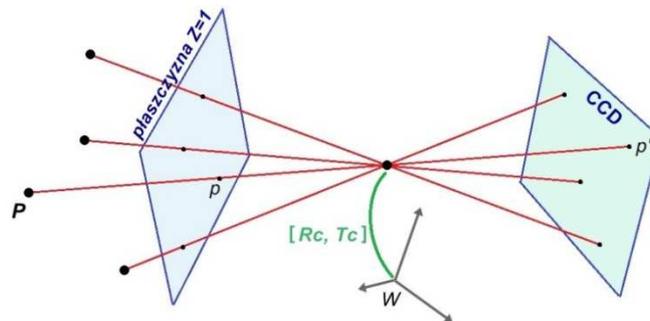


Fig. 3. Calibration of intrinsic parameters using chessboard pattern

Fig. 4. Calibration pattern points  $P$  and their projections  $p'$  including camera extrinsic parameters

on the CCD (Fig. 4) [4]. A group of  $p$  points can represent characteristic points on a precise calibration pattern, e.g. chessboard corners or circular dots. The camera model is obtained iteratively by minimizing the so called *reprojection errors*, which mean the deviations of projected on CCD points to their modeled equivalents on image (Fig. 5). Therefore, intrinsic parameters are strongly depended on calibration pattern precision, as well as points detection accuracy on images [5].

$$p' = Hp \quad (1)$$

where:

$$H = Ac[Rc | Tc] = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \quad (2)$$

$$Ac = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

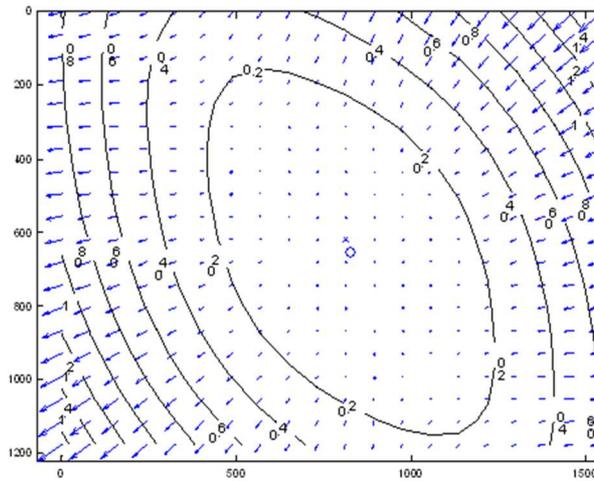


Fig. 5. Full model of camera distortions

For intrinsic parameters calibration a regular chessboard with the size of 600×450 mm has been used, mounted on a rigid aluminium frame (Fig. 3). The

main parameters have been computed using OpenCV libraries. This procedure can be performed outside the IMCM machine only once, or on demand in case of incorrect scanning results.

The extrinsic parameters have to be determined directly on the IMCM. Due to the long relative distance between cameras, a bigger calibration pattern needs to be used. Moreover, the calibration pattern must be precisely mounted on the IMCM frame in well established position relatively to machine coordinate system (Fig. 6). This allows to scan and measure markers in the common coordinate

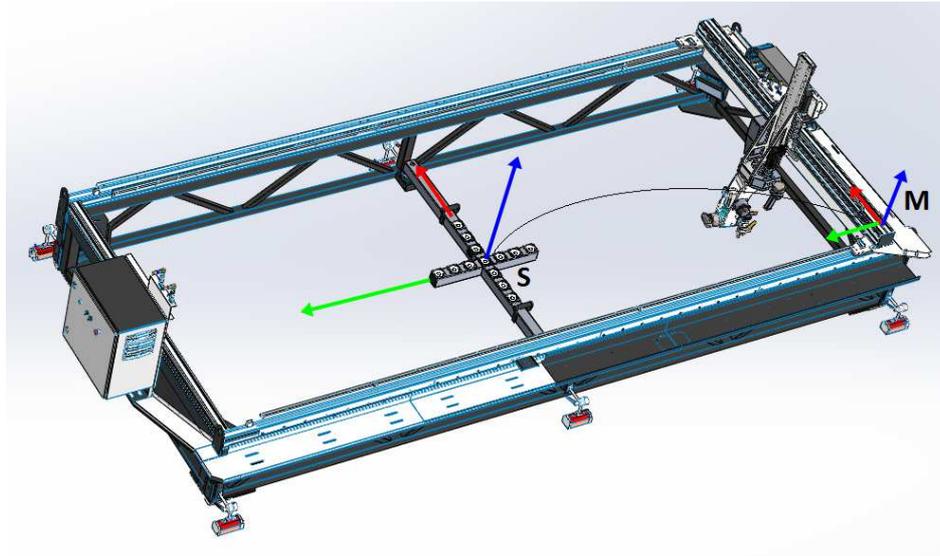


Fig. 6. 3D visualisation of the IMCM machine with calibration cross positioned in known relation to machine coordinate system

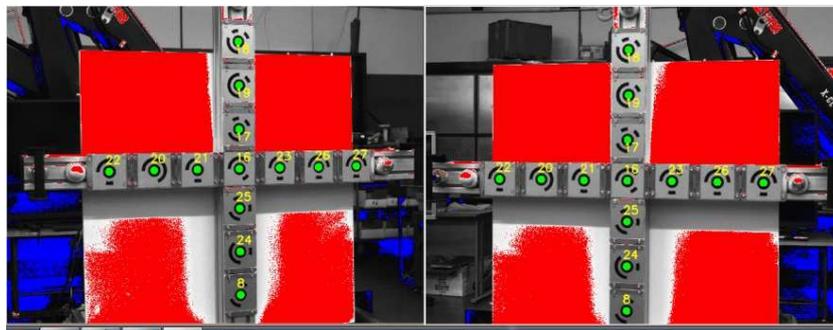


Fig. 7. Real-time coded marker recognition on cross for extrinsic parameters. with low- and over-exposed areas colored

system both for scanner and the IMCM. The calibration pattern has been constructed in the shape of regular cross (Fig. 7), carrying a group of coded markers on each arm (Fig. 8). The relations between all coded markers and mounting bolts have been calibrated by the use of GOM Tritop photogrammetry system.

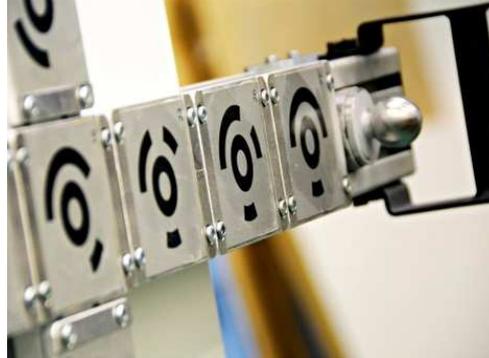


Fig. 8. Calibration cross with reference spheres for the IMCM

## 6. The scanning head

Repeatable measurement results can be achieved only for stable temperature conditions. The first research stand has been located in stable conditions and single calibration of camera intrinsic parameters has been required to operate constantly. The cameras have been mounted directly without any sort of insulations. In real conditions the cameras have to be ready to operate quickly, thus they should be isolated from environmental factors like temperature and humidity. An optimal temperature for intrinsic parameters calibration and normal working of the cameras is assumed to be 30°C. For the first prototype of scanning head a pair of hermetic casings equipped with internal air-heat circulation and moisture absorber have been constructed (Fig. 9).

Differently, it was required for the projector casing to apply a small amount of air overpressure to avoid dust accumulation and general overheating. The cameras, as well as projector have been mounted on a common solid aluminium beam, attached to the IMCM (Fig. 10). Their positions and orientations have been determined for simultaneous illumination and observation of the same, possibly large workspace.

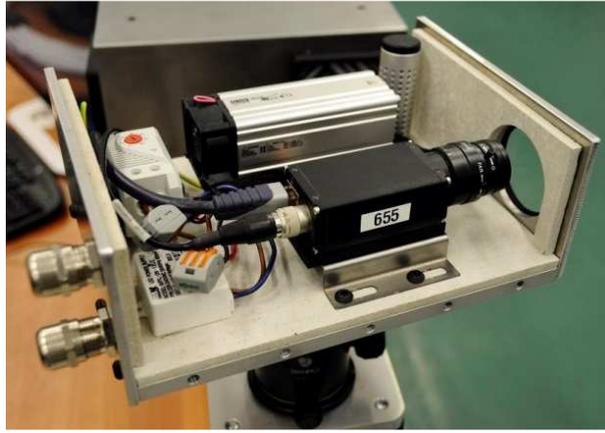


Fig. 9. Camera casing with internal insulation, air heater, thermostat and humidity absorber



Fig. 10. Scanner head consists of two camera modules and projector module mounted on common beam

## 7. Structured light techniques

The most effective method, commonly used in almost all fast commercial scanning systems, is the projection and recording of regular raster, illuminating the scanned object. This raster can have the form of parallel fringes with the variable width, positions and intensity (Fig. 11). A special combination of Gray Code fringes has been designed and adopted in the system. Combining a series of images by qualifying of each pixel logical state, an individual bit-codes for narrow pixel stripes are assigned [6] (Fig. 12). Width of the code stripe is dependent on camera resolution and lens quality.

Further coding within a single code stripe is possible by use of technique called *phase shifting*, which involves projection of additional sinusoidal wave patterns (Fig. 13).

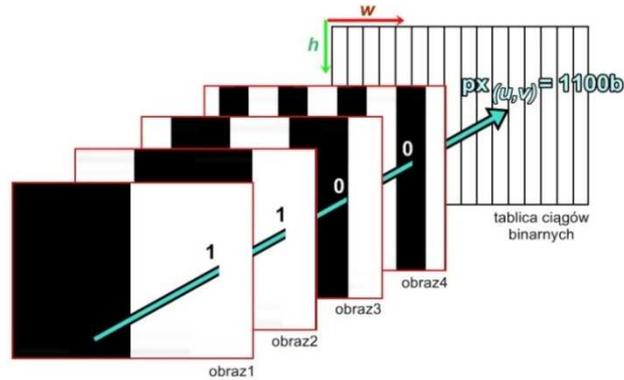


Fig. 11. Binary images prepared for the projector

obraz 1	0				1			
obraz 2	1		0				1	
obraz 3	1	0	1		0	1	0	1
obraz 4	1	0	1	0	1	0	1	0
...								
obraz n								
pasma kodowe								
	0111	0110	0100	0101	0000	0010	0011	1011
								1010
								1000
								1001
								1101
								1100
								1110
								1111

Fig. 12. Gray Code patterns forming unique binary codes

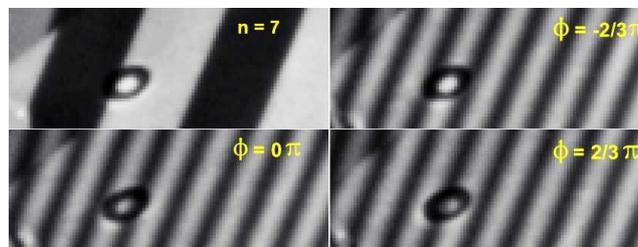


Fig. 13. Last four sequences of structural light projection in small selected area. The phase shifting is visible

Analyzing the pixel intensity changes (pulsations) for minimum three phase shifted sinusoidal patterns, the so called *wrapped phase map* can be obtained,

which describes the spatial point relations along the camera axis in radian units [7] (Fig. 14). Finally, knowing the intrinsic and extrinsic parameters for camera and projector, knowing the phase map and projection angles for each code stripe, and reconstructing the run of the light rays from projector to CCD, the *depth map* in mm units for each pixel can be determined. The great advantage of phase shifting technique is the tolerance for background intensity changes, treated as the fixed component of an image. It is only important to avoid exceeding the camera exposure by observing the most illuminated area of an object. For this purpose two colored images representing low- and over- exposed pixels were applied in the user interface (Fig. 6).

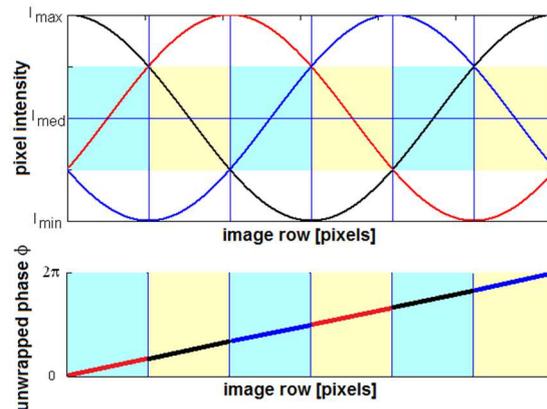


Fig. 14. Three sinusoidal wave combination, creating wrapped phase  $0-2\pi$

In modern 3D scanners all devices need to be calibrated, including the projector of fringe patterns. The projector parameters can be determined similarly to a single camera. Unfortunately, there are lot of difficulties during the reconstruction of images „captured” by the projector. The existing techniques require the illumination of common calibration pattern by horizontal and vertical fringes and recording all images by the nearest camera. Then a special pixel-by-pixel transformations from the CCD sensor to DMD matrix need to be performed using phase maps correspondences [7, 8].

In particular case of the IMCM the wide angle projection has been proposed, which places high demands on calibration and could cause plenty of errors of image reconstruction. It has been decided to introduce a different technique, based on two calibrated cameras and non-calibrated projector (Fig. 15). Special fast algorithms for analysis of four phase maps have been developed in C-code and tested on IMCM machine. Finding the corresponding pixels with very similar phase coordinates (Fig. 16), the procedure of 3D point reconstruction can be performed. This method, combined with epipolar geometry and special dynamic

filtering, has turned out to be effective and has resulted in high resolution 3D point cloud in only few seconds (Fig. 17 and 18).

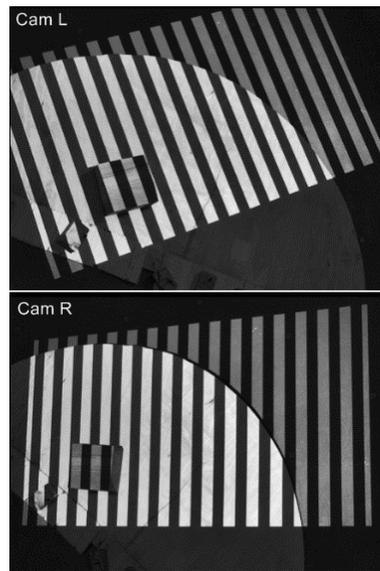


Fig. 15. Fringes projected on scanned surfaces visible from two cameras

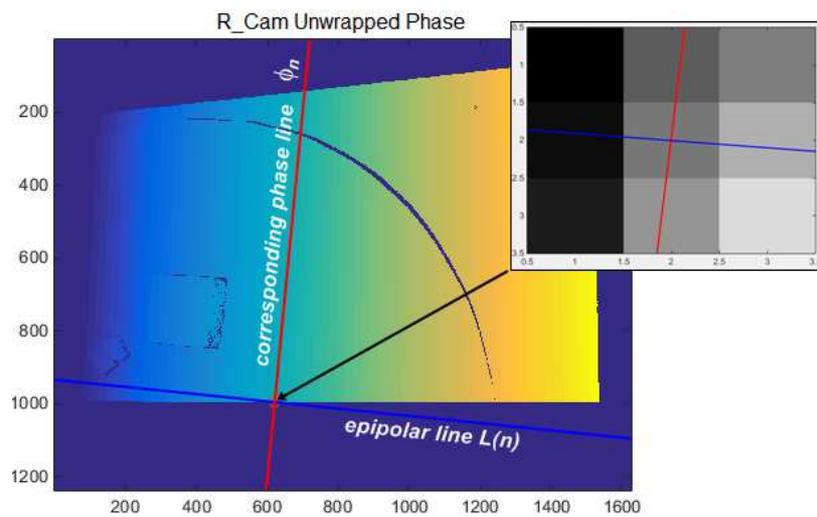


Fig. 16. Example of unwrapped phase map. The rounded edge and metal test blocks are visible

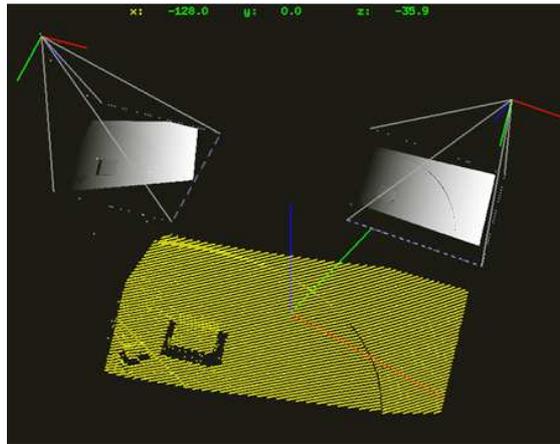


Fig. 17. 3D reconstruction based on only two calibrated cameras and phase maps (visualized in camera cones)

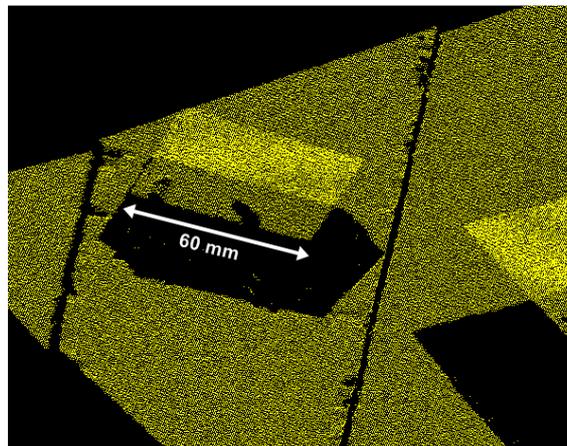


Fig. 18. Zoom in the scanned surface. High density of point cloud captured from distance of 1.3 meters. The damages of steel plate edges clearly visible

## 8. Procedures of markers detection

Measuring of large scale object by use of single scanning head is possible through applying partial scanning and matching the overlapped areas. Another way is to use some additional reference points (markers) attached to the object which create 3D reference grid (Fig. 19). The flat, round markers were proposed for scanning, as well as for calibration. This kind of markers can be equally illuminated and always appear as high contrast regular shape on image.

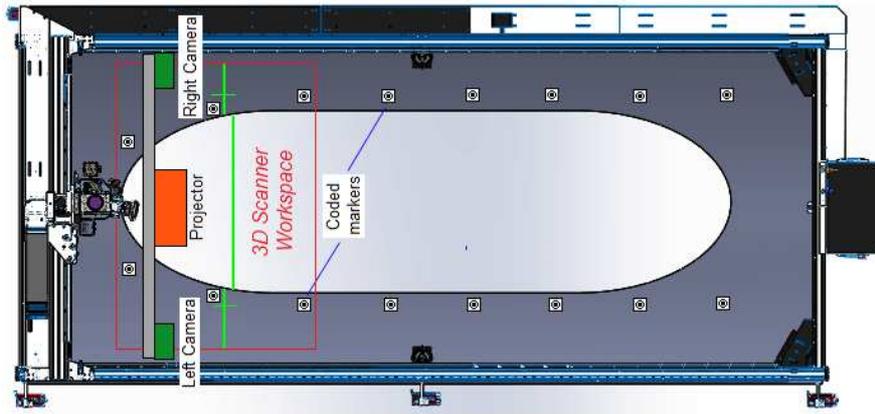


Fig. 19. A view of the IMCM model over the scanned surface. Concept of partial scanning by use of coded markers along the hole edges

Furthermore, the binary code sequences have been placed around the circular area (Fig. 20), which allow to distinguish each marker among the others in order to avoid incorrect point cloud transformation while scanning on the IMCM. The proposed algorithm searches the objects with common centers of gravity, then fits the exact ellipse model [9] and recognizes the code sequence (Fig. 21). The 7-bits Gray Code has been applied, as a compromise between the -marker size and code recognition efficiency. Skipping the combination of segments for unique *start sequency*, it is possible to create 54 different markers. Several tests have been performed to define best marker's shape and proportions and to assess detection efficiency and resistance to improper illumination (Fig. 22). This kind of markers can be successfully attached on the magnets to the steel objects welded on IMCM.

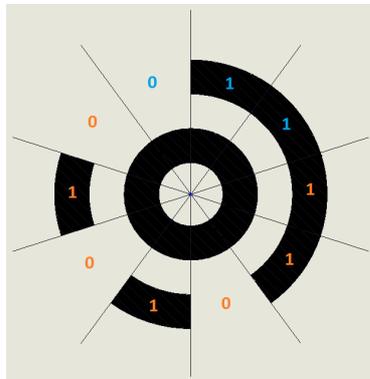


Fig. 20. Code-sequence (orange), and start-sequence (blue) around circular marker

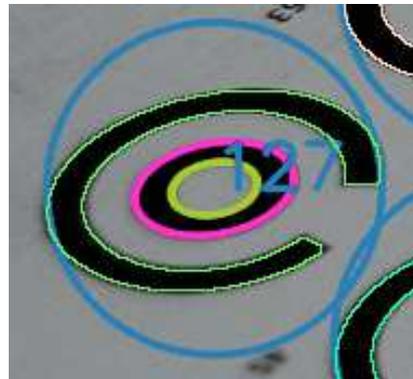


Fig. 21. Correct detection of central marker and code fields for proper exposure setup

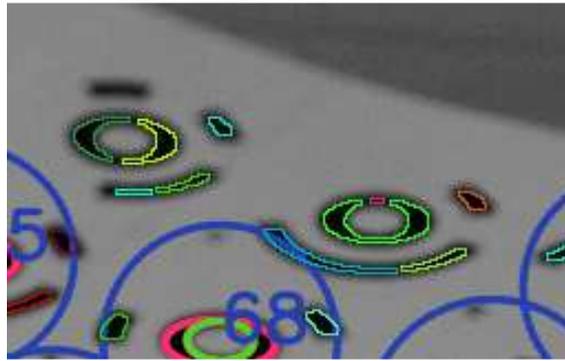


Fig. 22. Incorrect marker detection caused by blurred image and too long distance from the camera

## 9. Edge detection

One of the most critical aspects of the conducted research is edge detection of the scanned geometry, especially the edges along holes. This edge can be transformed into trajectory for the welded tool. In image processing several algorithms for edge detection exist, based on derivative analysis. e.g. Roberts, Prewitt, Sobel, or based on gradient filtering, e.g. Canny [10].

Edge recognition on the image is possible due to illumination changes, but could cause errors when shadows, roundings or rapid structures changes occur (Fig. 23). For the IMCM solutions, in the first step Canny filter has been applied

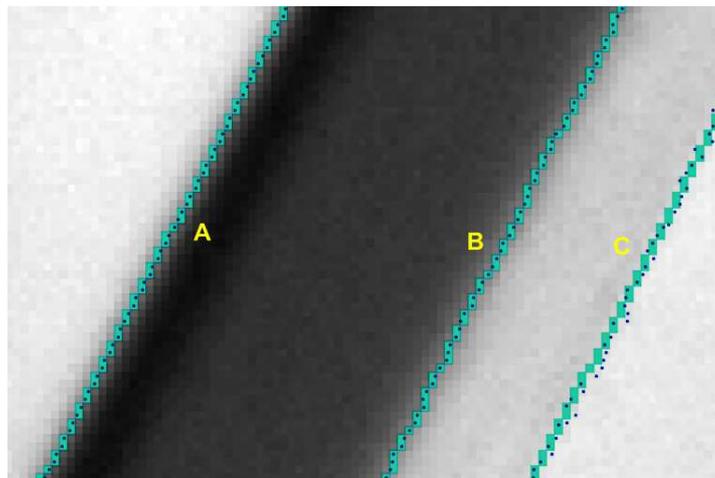


Fig. 23. Detection of three different edges. A) real material edge, B) shadow edge, C) Edge on material binding. Canny filtering results in green pixels. The additional sub-pixel algorithm results in black „dots”

to detect all potential edges. The second step involves structured light techniques and the algorithm for phase map analysis as well as specified phase jumps detection. Both methods complement one another and allow to find all the edges within the hole, independently on the illuminations with the accuracy of one pixel. The third step is to reconstruct this edge with sub-pixel accuracy using nearest neighborhood for selected and reconstructed point.

Due to high temperature occurring by steel cutting the high material distortions could appear, which complicate further welding along preplanned tool path. The corrections of the path based on scanned edge have been proposed. Thus, the vision system could become an alternative solution for the contact sensor or currently used laser probe.

## 10. Experimental results

Before the first experiments both models of wind turbine elements have been scanned using the commercial GOM Atos system. The results, treated as reference, have been used to find geometric features like axis direction, diameters, cone angle and the cutting hole edge (Fig. 24 and 25). Moreover, the obtained geometry can be further used to compare scanning results with the IMCM scanner.

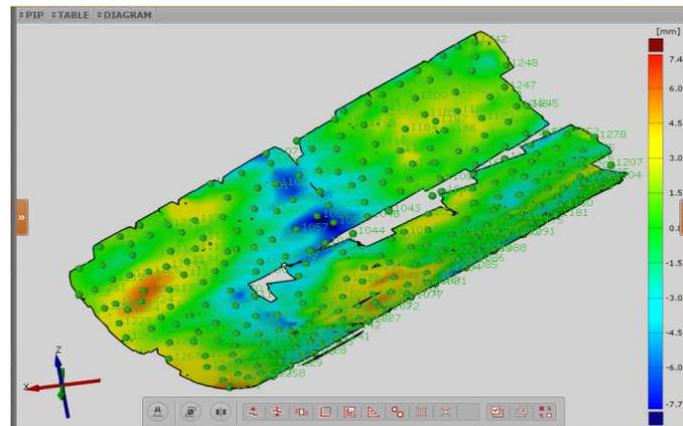


Fig. 24. Deviations map in reference to aligned cone.

In the next step similar measurements for specified area have been performed using the research stand. The two small areas with and without the hole edge have been selected (Fig. 26). Obtained results allow to assess the effectiveness of image processing algorithms for various conditions and system settings. All potential sources of errors in the term of 3D reconstruction have been estimated and adopted to the prototype of the IMCM scanner. All the initial studies on 3D scanning have demonstrated that the obtained accuracy and resolution of the 3D data are



### Acknowledgements

This work has been supported by the National Centre for Research and Development (NCBiR) within the INNOTECH programme (no. INNOTECH-K3/IN3/25/227427/NCBR/14), project „Smart and portable system for cutting holes and welding components in steel spatial construction”.

### References

- [1] R. ŁABUDZKI R., S. LEGUTKO: Applications of machine vision. *Manufacturing Engineering*, **10**(2011)2, p. 27-29.
- [2] H. GOLNABIA, A. ASADPOURB: Design and application of industrial machine vision systems. *Robotics and Computer-Integrated Manufacturing*, **23**(2007)12, p. 630-637, December 2007.
- [3] <http://www.promotech.eu/en/products/5-axis-portable-cnc-cutting-and-welding-machines/>.
- [4] T. LUHMANN, S. ROBSON, S. KYLE, I. HARLEY: Close range photogrammetry: principles, methods and applications. Whittles Publishing, London 2006.
- [5] S. ZHANG, R. CHUNG: Grid point extraction and coding for structured light system. *Optical Engineering*, **50**(9), 2011.
- [6] E.A. RAGLAND: Direction-sensitive binary code position control system. U.S. Patent 2823345, 1958.
- [7] S. ZHANG: High-resolution, real-time 3-D shape measurement. PhD thesis, Stony Brook University, Song Zhang, China 2005.
- [8] S. ZHANG, P.S. HUANG: Novel method for structured light system calibration. *Optical Engineering*, **45**(2006)8.
- [9] L. BAOZHANG, C. YANPING: Edge subpixel location of ellipse in computer vision measurement. Proc. 3rd Inter. Conference on Advanced Computer Control, Harbin, China 2011.
- [10] G.T. SHRIVAKSHAN, D.C. CHANDRASEKAR: A comparison of various edge detection techniques used in image processing. *International Journal of Computer Science Issues*, **9**(2012)1.

*Received in November 2016*