3D Object Digitization Devices in Manufacturing Engineering Applications and Services

doi:10.2478/mape-2020-0038
Date of submission to the Editor: 03/2020
Date of acceptance by the Editor: 06/2020

MAPE 2020, volume 3, issue 1, pp. 450-463

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INTRODUCTION

Dynamic development of devices for digitizing 3D objects has opened up new possibilities of using this technology in the implementation of manufacturing processes. Digitization of 3d objects is used in such branches as medicine, production of computer games and films, sports, etc. Until recently, digitization of 3D objects was possible thanks to 3D scanners, which were expensive devices. According to the forecast made by Allied Market Research, the value of the 3D scanner market was to reach 5 mld USD in 2013-2020. However, in 2017 this value was 8 mld USD, which significantly exceeded the initial assumptions. Currently, it is expected that the value of the 3D scanner market in 2025 will amount to 53 mld USD. The wide development of mobile devices, optical sensors and IoT devices meant that engineering projects for the construction of inexpensive and effective scanning solutions began to appear. They are a compromise between device price and quality, but in some areas they can be an interesting alternative to expensive scanning devices (Salwierz, Szymczyk; 2019).

The article aims to review the available technologies for digitizing 3D objects and to compare them in the context of individual application areas. It presents selected tools and software that will economically and efficiently increase the range of applications of digitization methods in the production process and offer various services on the market.

3D SCANNING METHODS

The operation of the scanner is based on collecting information about the point cloud of an object, which is then transformed into a three-dimensional model. The most popular scanning devices in an affordable price class are based on

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two basic principles. Either the camera lens detects light reflected from the object (non-contact scanners), or the information about the object is obtained from a probe that traverses the surface of the object (contact scanners). During contact scanning, the object is firmly attached to a flat surface. The scanning itself is provided by a special pressure-sensitive probe, the current position is determined by the CCM (Coordinate Measuring Machine) technique. Contact scanners can be:

- placed on a measuring arm that is moved by a human (used, for example, in animation studios),
- part of a robotic arm (automated, repeatable processes in industrial production),
- manual (used in the field).

The non-contact scanning method is more popular and more convenient for the user. The currently used 3D scanners are most often based on optoelectronic technology, i.e. the technology that uses the properties of light to collect, transfer and present information. Object scanning involves the projection of many different white light structures onto the object being digitized. These structures differ from each other in the number, density and position of lines, and straight lines are distorted by the measured object. The 3D scanner therefore works on the principle of spatial collection of information based on the coordinate measuring technique. It enables detailed and non-contact determination of the dimensions of spatially shaped objects, i.e. the analysis of the shape of the object and the conversion of the obtained data into a visualized digital object. The technique of this measurement is characterized by basing the scanning process on the coordinate values of the localized measurement points that make up the body of the analyzed object. The data processed as a result of scanning are sent to the computer and presented in the form of a three-dimensional model. One measurement allows you to collect even several million measurement points per second, thanks to which it is possible to quickly map even the most complex geometry. Often, additional scans, for example from a different perspective, are required to completely scan an object. The combination of the collected 3D scans is then performed by computer programs and specially designed algorithms. The most popular methods of optical scanning include:

- scanning with a laser beam,
- visible and infrared structural light,
- photogrammetry.

The active optical scanner obtains information about the position and shape of an object on the basis of triangulation. Triangulation is the calculation of the intersection of a plane and a ray in space. Each point in the camera image has a certain ray of light (ray). There is a plane corresponding to each projection of the column of the projector's pixel centers (or a row when the projector is shifted vertically with respect to the camera). Knowing the equations of the rays corresponding to the camera image points and the planes corresponding to the columns illuminating these points, you can recreate its position in space. The solution presented in this paper uses a lateral shift, so in the further discussion we assume that the patterns are vertical stripes. The scanner takes photos of the object illuminated with special patterns. The patterns allow you to assign the image dots to the projector's image column number. On the basis of these data, the position of the projector in relation to the camera and the parameters of the lenses of these devices, it is possible to recreate the equations of rays and planes corresponding to the points in the image. This process is described in detail below and illustrated in Figure 1. (Salwierz, Szymczyk; 2019, Wrona, Piotrowska; 2015, Nowacki et al.; 2018)

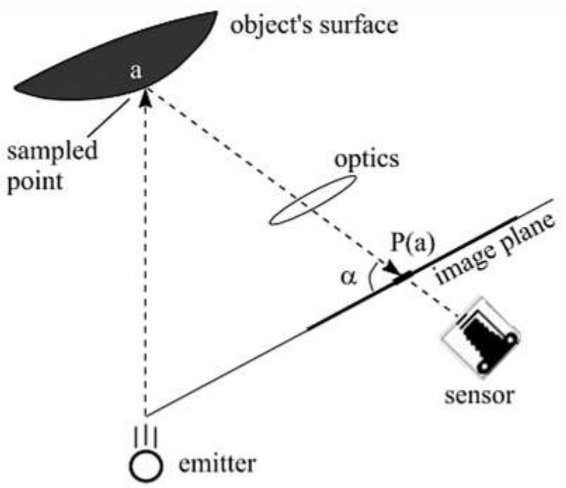

Fig. 1 The principle of three-dimensional scanning

Source: (Rocchini et al. 2001)

The presented method belongs to the so-called Active scanning methods that require the use of an external laser or structured light source. Passive methods do not require lighting with structured light and are based on the interpretation of photos of the scanned object (e.g. photogrammetric or stereophotogrammetric methods). (Rocchini et al. 2001) Currently, other methods of 3D scanning are also used, using optical methods. The division and taxonomy of the scanning methods are shown in Figure 2.

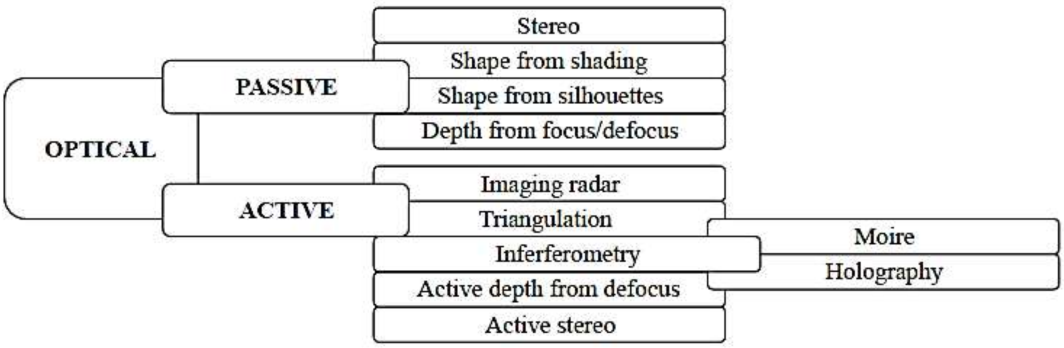

Fig. 2 3D scanning methods

Source: Own elaboration based on: (Rocchini et al. 2001)

OVERVIEW OF SELECTED SCANNING DEVICES AVAILABLE ON THE MARKET

There are many different 3D scanning devices on the market. In addition to the differences in the scanning technologies used, there are differences in the accuracy and speed of the devices, which translates into their price. Below are some examples of this type of device.

3D Scanner 1.0A from XYZprinting

Scanner 3D 1.0A from XYZprinting is the most affordable solution from the Taiwanese manufacturer. This solution offering four modes of scanning. It uses Intel RealSense Camera technology to scan areas of 60 x 60 x 30 cm, 80 x 50 x 80 cm or 100 x 100 x 200 cm. The scan resolution is between 1.0mm and 2.5 mm, keeping in mind that the operating range is 50 cm. The device uses structured light technology and the measurement frequency is 30fps. The manufacturer also provides XYZ Scan Handy (Fig. 3), a scanning and post-editing software to edit your models after scanning. The price of the scanner is around $300 (3dnatives.com).

Fig. 3 3D Scanner 1.0 A from XYZprinting

Source: (3dnatives.com)

SOL 3D Scanner from Scan Dimension

SOL 3D Scanner was developed by Scan Dimension in Denmark (Fig. 4). This device is essentially a hybrid solution, because uses a combination of laser triangulation and white light technology to 3D scan real-life objects. The camera picks up the texture, the laser collects its geometry.

Fig. 4 SOL 3D Scanner from Scan Dimension

Source: (3dnatives.com)

This scanner can provide a resolution of up to 0.1 mm with texture feature and a scanning area of 100 x 100 mm, while the far scanning mode provides a

scannable area of 170 x 170 mm. The 3D scanning process is automated and you can choose between a near and far scanning mode.
The SOL 3D (Fig. 4), scanner also includes software to simplify your entire workflow. In a few steps you will be sending your 3D model to your 3D printer. This is a solution meant for makers, hobbyists, educators and entrepreneurs who may not have the most experience with 3D scanning devices but still want to achieve great results. The SOL 3D scanner retails for $700 (3dnatives.com).

Matter and Form 3D Scanner V2 (MFS1V2)

The Matter and Form V2 3D (Fig. 5), scanner from Canada is a desktop 3D scanning solution powered by MFStudio software. Based on laser triangulation technology, the accuracy on this device can reach 0.1 mm with the precision of these eye-safe red lasers. The Quickscan feature captures geometry in as fast as 65 seconds. Packaged together with the V2 3D scanner, MFStudio and Quickscan produce rewarding, fast results that allow you to set up a scan. Supported on both Windows and Mac, with multiple export capability for 3D printing. It enables scanning an object with a maximum height of 25 cm and a diameter of 18 cm. The 3D scanner is available from $750. (matterandform.net, 3dnatives.com)

Fig. 5 V2 from Matter & Form

Source: (matterandform.net, 3dnatives.com)

EINSCAN-SE from Shining 3D

The Einscan-SE scanner from the Chinese manufacturer Shining 3D is characterized by its short scanning time and ease of use (Fig. 6). This scanner is an efficient entry level designed to capture the geometry of small and medium sized objects in three dimensions. It is based on structured light (white light) technology and offers two 3D capture modes: Constant Scan and Auto Scan. The auto scan mode uses a rotating table. The scanner has a 1.3 megapixel camera that can capture the colors and surfaces of the object being scanned. This 3D scanner is capable of capturing fine details with high resolution (0.17mm point distance) and provides an accuracy of 0.1mm. For a single scan, the machine takes about eight seconds, and a 360° scan in the auto scan mode takes two minutes. Objects up to 700 x 700 x 700 mm can be scanned in the free scan mode, and up to 200 x 200 x 200 mm in the auto scan mode. This is the most affordable 3D scanning solution from the manufacturer. The starting price of the EINSCAN-SE is $1,400 (einscan.com, 3dnatives.com).

Fig. 6 EINSCAN-SE from Shining 3D
Source: (einscan.com, 3dnatives.com)

SLS Pro S3 from HP

The SLS Pro S3 from the American manufacturer is a professional scanner based on structured light technology. It is a further development of the DAVID SLS-3, originally manufactured by DAVID Laser scanner, a brand that was taken over by HP in 2016. With a scan size of approximately 30-500 mm and a resolution of up to 0.05 mm, the scanner can perform single 360° scans within seconds.

The HP 3D HD Camera Pro detects the patterns beamed out by the projector to generate 3D models of physical objects. The camera allows you to measure the RGB properties of an object to create color textures that can be viewed or turned off with ease. Besides a full-HD camera, the package includes adjustable metal stands and a tripod (Fig. 7). The software allows you to export 3D models in common file formats, such as obj, stl and ply, that are compatible across a wide range of popular 3D CAD programs. The device is currently available for purchase at a starting price of $3,995. (3dnatives.com, hp.com)

Fig. 7 EINSCAN-SE from Shining 3D
Source: (3dnatives.com, hp.com)

Eva Lite from Artec 3D

Artec 3D, based in Luxembourg, offers with the Eva Lite its cheapest option for 3D scanning. This professional scanner is specialized in the digitization of complex geometries, such as the human body, and is therefore increasingly

used in the medical field. It works on the basis of structured light technology and, although it does not have the ability to capture colors and textures like most scanners of the brand, it has an accuracy of 0.5 mm.
This 3D scanner works with the software package Artec Studio (Fig. 8). Artec Studio is a powerful tool for an optimized 3D scanning process. This software is able to perform, assemble and repair 3D scans. It is currently available at a price of $9,800. (3dnatives.com, artec3d.com)

Fig. 8 EINSCAN-SE from Shining 3D
Source: (3dnatives.com, artec3d.com)

Evatronix eviXmatic

EviXmatic is a high-quality 3D scanner introduced to the market by the Polish manufacturer Evatronix SA (Fig. 9). This scanner is designed to perform repeatable measurements in the quality control process. An example application is a production line on which objects with complex shapes are produced. The device can use scanners eviXscan 3D HD Quadro and HD Optima. The more advanced of the two, the HD Quadro has both wide and fine measuring ranges, between 370 × 265 × 150 mm and 210 × 145 × 90 mm respectively, delivering a point density of 50 pt/mm² or 161 pt/mm². Operating an RGB light source, it has 4 x 5 Mpix cameras, and is capable of producing an accuracy of up to 0.0130 mm.

Fig. 9 EINSCAN-SE from Shining 3D
Source: (aniwaa.com, artec3d.com)

The HD Optima, on the otherhand, uses a Blue LED lightsource, and have 2 x 5 Mpix cameras. Its measuring range is 250 × 170 × 120 mm (116 pt/mm² point density) with an accuracy up to 0.0183 mm. It integrates a powerful software, Geomagic Control X, which allows you to com-pare 3D scans with a reference CAD model to detect potential part flaws. If necessary, the scanner integrated with the eviXmatic system can be disconnected and used independently. The scanner uses structured light technology. Its price is in the range of $10,000 to even $50,000.

MOBILE AND IOT DEVICES IN THE CONSTRUCTION OF 3D OBJECT DIGITIZATION SYSTEMS

David Laser Scanner is one of the developing open 3D scanner projects. The system is an open project constantly developed by the user community. It uses reference panels in the form of printed A4 sheets with a pattern in the form of dots. These dots are the reference plane for the software that analyzes the reference system and compares it with the image obtained from the camera. The information that the reference dots form lines at an angle of 90 degrees simplifies image analysis. The object placed on their background, on which the laser beam falls, "bends" this line according to its shape, thanks to which it is possible to detect information about the shape of one "slice" of the scanned object. By scanning the entire object with such a laser line, the program combines all these curves layer by layer, which allows the final process to create a model. One of the modifications to this design is the use of special line patterns instead of laser lines, which are displayed by the projector. This results in better scanning accuracy and the quality of the final models. The downside of this technology is the need to use the reflected light from the object in the scanning process, which is not always possible to achieve. Glossy objects or glass will not always work well with this technique. The basic version of the David system is free, the software allows saving in a reduced resolution. On the basis of this project, many modifications were created that allow the implementation of 3D scans in good quality. A demonstrative drawing showing the operation of the scanner is shown in Figure 10. (Chen et al., 2013)

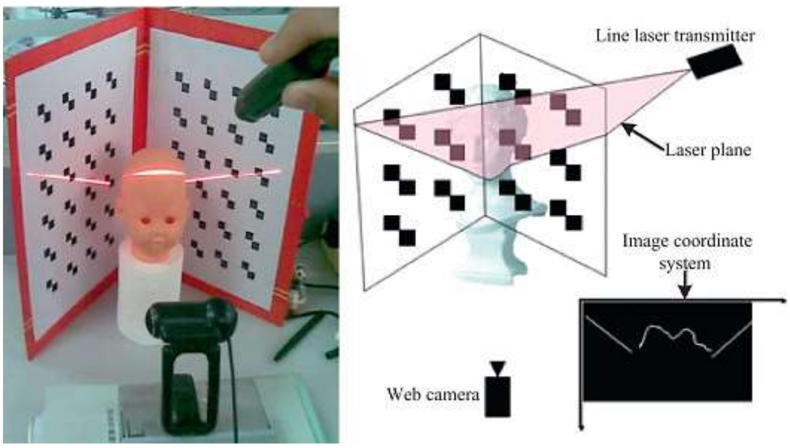

Fig. 10 Construction of the David Laser Scann

Source: (Chen et al., 2013)

Another solution is the 3D scanner presented on the forum of FORBOT users. It is a project made as part of a collective term paper of students, which has then been modified. The scanner works on the basis of a series of photos of an object that is illuminated with a laser ruler. Each image is thresholded and filtered to read the shape of the laser lines. The laser ruler points are remembered for each image. On their basis, the position of the object point cloud is calculated. The scanner has a rotating platform to facilitate taking a series of photos, so points are also recorded using cylindrical coordinates. Full operation of the scanning system requires prior calibration with a reference object of known dimensions in order to accurately reflect the shape being scanned. Taking into account the fact that the 3D scanner uses a red laser beam, all transparent objects are invisible to it, because the beam of rays does not reflect from the scanned object and does not fall into the camera lens. The same is true for black objects, where the radiation beam can be absorbed by the object to such an extent that, as before, the camera will not register the laser line. A demonstrative drawing showing the construction and operation of the scanner is shown in Figure 11 (Forum FORBOT).

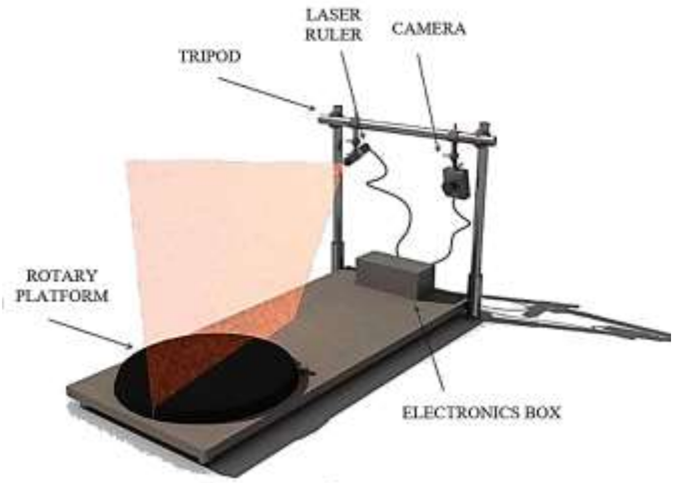

Fig. 11 Construction of the 3D scanner
Source: (Forum FORBOT)

Comparative studies of 3D scans made with the Kinect controller and professional 3D scanners are also available in the literature. The Kinect controller is a device that allows the detection of a human figure and, using additional software, to analyze his movements and use them to control the software (Fig. 12). The Kinect controller has been available on the Polish market since 2010, and its latest version is from 2014. Initially, it was intended only for the Xbox console, but subsequent versions also allowed for work with a PC with Windows 8.1 or newer operating system. Due to its structure, consisting of, among other things, an RGB vision camera, a depth camera measuring depth using structured light, and thanks to the possibility of recording 3D images, the Kinect controller quickly became a popular and cheap device for 3D digitization.

Microsoft has prepared an application for users called 3D Scan. The scanning process with this application and the Kinect controller is very simple, in two possible modes. If we want to scan a larger object, we can go around it holding Kinect in hand and then turn on the so-called manual mode. We can also put the item on a rotating table, Kinect on a tripod and turn off the manual mode. Before that, we also choose the size of the object we intend to scan. In order to obtain the best possible scanning results, the computer to which the Kinect controller is connected should be equipped with a 64-bit dual-core processor with a minimum clock speed of 3.1 GHz, 4 GB of RAM, NVidia CUDA graphics card and a USB 3.0 port. (Buchwald; 2019, Podlasiak; 2012)

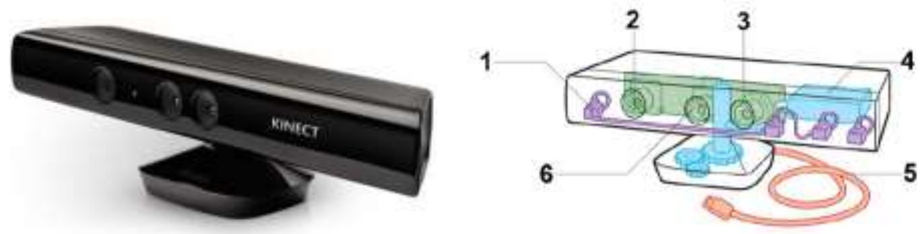

Fig. 12 Kinect controller
1 set of microphones, 2 infrared emitter, 3 infrared camera, 4 automatic tilt controller, 5 connection cable, 6 RGB camera
Source: (Podlasiak; 2012, Rembała; 2013)

The trueDept technology can also be used to digitize three dimensional objects. It is an Apple solution integrated with Apple's mobile devices. Apple has used solutions from acquired Primesense and Faceshift over the past few years to place a depth sensor in every front camera on new iPhones. This system is designed for facial recognition to log into the phone automatically using the Face ID system. There are also applications that allow the use of this technology as a 3D scanner. One of them is the free Capture: 3D Scan Anything application that allows you to capture and 3D scan any object using the same camera. Since it is the front camera, you need to hold the iPhone screen facing the object being scanned. The scans you perform are saved in Apple's USDZ format on iOS devices and can be shared with other iPhone users via Messages in this format. 3D object scan, can also be converted to the popular vol format.
ToF sensors are also becoming more and more popular among users of mobile devices. The ToF 3D sensor is one of the solutions used by smartphone manufacturers for frame mapping. It is based on the time of flight technology, i.e. measuring the time that the generated light beam needs to return to the sensor after bouncing off the object. These types of sensors use LED or laser illumination and advanced algorithms that based on the constant speed of light – determine the distance from the sensor to the objects. ToF 3D enables the creation of a 3D frame map with high accuracy. There are also other 3D scanners available on the mobile market, including solutions based on structured light (recently introduced in Honor Magic 2 3D), which in theory guarantee more accurate 3D maps of the frame, but time of flight also has an

important advantage over them. ToF 3D stands out due to its speed of operation compared to other laser sensors. A lot of shots are created in a second, which can be used, among others for tracking the movement of objects in the frame, and for creating 3D models of objects.
Currently, there is also software that allows you to use a mobile phone as a 3D scanner using photogrammetry. Photogrammetry (or SFM – Structure From Motion) is a process that calculates the three-dimensional coordinates of the surface points of a real object from photographs taken at different angles. Photogrammetry (or SFM – Structure From Motion) is a process that calculates the three-dimensional coordinates of the surface points of a real object from photographs taken at different angles. You can take several photos of an object from all possible angles, then use the photos as input to create a 3D model. The software will compare the photos in terms of similar areas trying to match the places from which the shots were taken. Knowing the location of the camera and its direction, you can create points of the 3D model that correspond to the two-dimensional data from the image (i.e. simply pixels).

EXPERIMENTAL EVALUATION OF 3D SCANS WITH THE USE OF SELECTED TECHNOLOGIES OF DIGITIZATION OF OBJECTS

One of the assessed possibilities of digitization of three-dimensional objects was scanning the workstation with the use of the photogrammetric method and meshroom software. It is a free software for the implementation of 3D models using the photogrammetric method. Meshroom requires a CUDA (Compute Unified Device Architecture) matrix to run. It is a universal architecture of multi-core processors (mainly graphics cards) developed by Nvidia, enabling the use of their computing power. For this purpose, 60 photos of the scanned object were taken at different angles. The photos were taken manually without an additional tripod or a device allowing to constantly rotate the scanned object by a given angle. A Huawei P Smart 2019 device with the following camera parameters was used to take the pictures: 13 MP, f/1.8, with the PDAF function (phase detection autofocus). The following general assumptions were used when taking photos:

- The photos showing the entire object that we want to present.
- The photos show as much of the object as little background as possible.
- Permanent lighting throwing as few shadows as possible.
- No moving objects in the background.
- The worse the object reflects the light, the better.

The quality of the resulting 3D model had a big impact lighting. The formation of shadows meant that they were interpreted as an element of the object. The best results were obtained with daylight. Creating a 3D object using the HP ProBook 450 G5 2RS27EA laptop – Intel Core i7 8550U/8 GB/(256 M.2 SSD + 1000 HDD) GB/nVidia GeForce 930MX took about 15 minutes. A 3D scan of the photographed object was obtained. The 3D scan preview and the Meshroom software interface are shown in Figure 13. The created model was characterized by a shape discontinuity in certain places and required additional processing with external CAD software. Subsequent processing of the model took longer than the process of its scanning. This method turned out to be laborious, but the model obtained after manual corrections was satisfactory.

Fig.13 Meshroom interface while making a 3D model
Source: Own elaboration

CONCLUSION

The 3D scanners are devices that analyze an object or its surroundings in order to collect data on the shape or appearance (color). Based on this data, digital three-dimensional models are created. The market review for devices of this type made it possible to draw the following conclusions.

The choice of 3D scanners is very wide, the devices differ in terms of the technologies used (contact, non-contact, active, passive technologies, using laser light, structured light, ultrasound, sensors, etc.) as well as accuracy and price. The quality of the scan is influenced by many aspects such as: the type of lighting (artificial, natural), the color of the surface of the scanned surface, the texture of the surface being scanned, the type and color of the laser used, the transparency of the surface of the scanned surface and the degree of light reflection. Currently, making precise scans using dedicated 3D scanners requires quite large financial outlays for both hardware and the necessary software.

Due to the broadly understood development of technology, in addition to dedicated 3D scanners, other devices can be used to create scans. One of such examples is the Kinect controller, whose main task was to detect the human figure and analyze its movements to control the software. Due to its construction, consisting of, among others, an RGB vision camera, a depth camera measuring depth using structured light and thanks to the possibility of recording 3D images, the Kinect controller quickly became a popular and cheap device for 3D digitization. The achieved results do not allow the use of this type of scanner in industrial applications. However, due to the sufficient accuracy of 1 cm, it can

be used in medicine. Currently, it is most often used in games, especially consoles.
Another example is the ToF 3D sensors used in mobile devices. The Time of Flight technology measures the time it takes for the generated light beam to return to the sensor after reflecting off the object. This type of sensors uses LED or laser illumination and advanced algorithms which, based on a constant speed of light, determine the distance from the sensor to the objects. Another example is the use of a mobile phone as a 3D scanner thanks to photogrammetry, i.e. the process of calculating the three-dimensional coordinates of the surface points of a real object on the basis of photographs taken at different angles. You can take several photos of an object from all possible angles, then use the photos as input to create a 3D model.
The review of 3D technology has shown that scanning three-dimensional objects can be successfully performed using dedicated scanners, but also other devices such as mobile phones or the Kinect motion sensor, while maintaining decent parameters of the obtained visualization.

ACKNOWLEDGEMENTS

„Publication supported by Own Schoolarship Fund of the Silesian University of Technology in year 2019/2020" (grant number 25/FSW18/0003-03/2019).

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Abstract: The rapid development of CAD 3D systems has led to the development of solutions enabling the physical achievement of the designed object, already at the design stage. Such a solution is the rapid prototyping method, intended for fast, precise and repeatable production thanks to additive technology. The first basic step of this method is a 3D scan. It is a technique that analyzes a real object in order to collect data about its basic (geometric) and additional (e.g. color) features. The collected data is used to generate three-dimensional, virtual models. Scanning can be performed in various ways using different devices. The aim of the article is to review the available technologies for digitizing 3D objects and to compare them in the context of individual application areas. It presents selected tools and software that will economically and efficiently increase the range of applications of digitization methods in the production process and offering various services on the market.

Keywords: digitization, 3D scanning, mobile devices, scanning methods, modern technology