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Testing the Suitability of Spatial Printing Technology for Engineering Applications (for Presentation of Topographic Surface)***

1. Virtual Images 3D and Three-Dimensional Physical Models

All designing activity has the general need of visualizing a final result – both for the designer and the user of the project. For an advanced audience, such visualizations are presented graphically in the form of orthogonal projections. An ordinary audience requires a more accessible form, similar to their everyday experience – the form of a central projection (perspective). At present, such images of designed objects are made using advanced graphic editors CAD and are built on monitors as realistic images, including lighting and meteorological and natural parameters. Such images have many advantages and are prepared using important achievements of modern computer technology, what creates the realism of the reproduced scene or sequence of scenes (when using animated images). There are, however, some flaws of this method of visualization – the reason, why we need to build physical models of the design objects.

Physical models, compared with the virtual images on the screen or with the drawing, have the following advantages:

- observing of such a model requires neither hardware nor a sequence of drawings,
- you observe the model using the principles of your everyday experience, as a real three-dimensional object,
- you can observe the model in real time from any site, there is the possibility of a detailed insight into the shape of the model surface,
- you can directly determine the spatial relationship between the component parts of the model.

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Creating physical models has one fundamental flaw – if made manually – they are expensive. But despite the cost, models of geographical space objects have been and are still being made. For example, one can mention models used for managing a city, architectural designs in the form of models, historical visualizations and models used for educational purposes. A separate field of application is the building of geographical space models for experimental purposes, e.g. models of river basins, carried out for simulations of flooding.

Nowadays the technology of automated creation of physical models is widely developed, although the cost of such models is still much higher than the drawn images using CAD editors. Physical models are necessary for visualization, whereas the model in a visual form reproduces the shape of an irregular object. They are also required as prototypes and physical parts in the design and maintenance of machines. Recently more and more such models have applications in natural fields.

In recent years a new technology of creating physical models is being developed – the technology of three-dimensional printing (3D printing). The name of this technology does not reflect faithfully the principle of the creation of a spatial object. The ordinary audience understands printing as producing a flat image on flat material – that is – operating in two dimensions (2D). But extending our concept to electronic circuits printing, that already have a significant third dimension, we shall be well on the way to understanding the principles of three-dimensional printing.

2. Three-Dimensional Printing Technology

Three-dimensional printing technology involves building a model of layers. Subsequent layers are superimposed on each other, but their shape is given in numerical form – according to the programmed design model. The layers are bonded together by various techniques, with the result that a stable, spatial model is created. The thickness of layers has a wide range of accuracy, from tenths to hundredths of a millimeter.

One of the most popular methods of modeling technology is the one developed by the company Objet. Polyjet, the mentioned technology method, involves the usage of synthetic resin (acrylic rigid or flexible) and is one of the few methods that can dispense different types of material (resin) during the printing process.

Another solution was used in the technology of Selective Laser Sintering (SLS), prepared by the German company EOS. It is about the selective laser sintering of thermoplastic polymers powders of chain construction. The advantage of this technology is the high strength of the models.

A very similar technology is the one called Digital Metal Laser Sintering (DMLS), also developed by EOS, based on selective laser sintering of powders, but in this case the material is metal. Models made using this technology are very accurate, durable and fully useful as parts of different machines of an atypical shape.

It is also important to mention other technologies:

- Three Dimensional Printing (3DP) – the technological process involves combining powder with a linking liquid, in this case one can develop color models;
- Laminated Object Modeling (LOM) – the layers of adhesive-coated foil are successively glued together and cut by laser, though in this technology the models do not have high durability;
- Solid Ground Curing (SGC) – the layers of photopolymer in or the synthetic resin are hardened using ultraviolet light;
- Fused Deposition Modeling (FDM) – the technology based on depositing the thermoplastic material in layers.

In Table 1 you can find summarized some of the characteristic attributes of the different technologies of creating the three-dimensional physical models based on bibliography [1] and [2].

Table 1. Typical characteristic attributes of selected technologies of creating the three-dimensional physical models

Name of technology	Source material of technology	Accuracy of the creating of model
Polyjet	resines (acrylic, synthetic)	lack of data
Selective Laser Sintering	powder of the polymer	0.1 mm
Digital Metal Laser Sintering	metal powder	0.02 mm
Three Dimensional Printing	powders and linked liquid	lack of data
Laminated Object Modeling	plastic foil, paper	lack of data
Solid Ground Curing	photopolymer, synthetic resin	1 mm
Fused Desposition Modeling	polymers	0.2 mm
The Buccaner	metal powders	0.4 mm

3. Selecting of the Test Base and the Measurement of the Source Objects

To test the 3D printing technology one had to select objects of geographic space that represent only topographic surface and the topographic surface associated with engineering structures. In the case of topographic surface it is important to have compact fragments of land with hillsides of greater slope, where the line of the biggest fall has the maximum diversified direction. These criteria are very well met not only by the tops of the local hills but also by the characteristic anthropogenic objects – the Kraków mounds, which have additionally the advantage that their topography is widely known. Therefore, those four Kraków mounds: Piłsudski Mound, Wanda Mound, Krakus Mound and Kościuszko Mound were selected for the test objects.

All four mounds were created on the basis of a circle and have the shape of an artificial topographic surface. However, they vary in terms of integration with additional structures, which are the encircling paths, and the walls of the fortifications in the case of Kościuszko Mound.

In order to get a wide analysis of the experience, the source data was obtained by different methods, using different technologies of situational and leveling measurements. This procedure allowed evaluating of the correlation between the reproduced accuracy of the model shape and the method of measurement.

The first object to be measured was the Piłsudski Mound. The measured points were designed in approximately equal distances, on the two edges of the paths created for visitors in order to reach the top of the mound. The two GNSS receivers were used (Javad, Triumph-1). The first receiver was placed on the top of the mound, the coordinates of which were measured before by the four-hour static satellite measurement. Then the receiver was restarted in the mode of the base station. With the second mobile receiver 270 points were measured with an average error of coordinates: situational 4 mm and leveling 11 mm. The whole measurement lasted approximately two hours. On this basis a three-dimensional model was created.

The next measurement was made on the Wanda Mound. Here GNSS technology was used, the RTK-GPS method. In this case, one receiver, also from the Javad company, received corrections from a reference station KRA1 of ASG EUPOS net, located about 8 km in a straight line from the object. This method made it possible to obtain 70 points with a situational accuracy of 13 mm and high accuracy of 17 mm.

To measure the Krakus Mound the laser scanning method was applied, using the terrestrial laser scanner Leica model C10. According to the technical specifications of the device, the angle error is 15^{cc} and the distance measuring error 6 mm + 2 ppm. One obtained clouds of points from nine stations of scanner. The most accurate scan mode was chosen to reproduce the test surface as faithfully as possible. The measurement was very time- consuming, in total it lasted about six hours. The scanning from one station required approximately 30-minutes.

Direct measurement of the Kościuszko Mound proved difficult to implement due to the presence of a large number of tourists. For safety reasons (safety of the measuring team and the equipment and because of the large slop of the mound) the direct measurement was abandoned. It was decided to use data from the airborne laser scanning (ALS). Airborne scanning reproduces with high accuracy a terrain shape, especially when it is not covered with high or dense vegetation. The topographic surface of the Kościuszko Mound meets these conditions; therefore the data obtained from these indirect measurements can be regarded as a fully valuable.

4. Data Preparation and the Performance of Three-Dimensional Physical Models using 3D Printing Technology

Universal batch format, preferred by most companies that are into a three-dimensional printing technology is *.stl (STereoLithography) format, also known as Standard Tessellation Language. In the file, in text or binary notation, you can find information about vectors limiting surface, which gets materialized. Most CAD software packages support *.stl files. For the purpose of our experiment it was decided to use a few different packages, GIS and engineering graphics CAD.

The measuring data of the Piłsudski Mound was elaborated using CAD Microstation Select Series 3. On the basis of 270 points a triangle network was generated. The model was verified for its correctness and then exported to *.stl format. A physical model, obtained from the 3D printing (Fig. 1), shows in a direct observation at first glance, no steep slopes of the conical surface of the mound. This is due to the generally applicable principles of engineering that intentionally exaggerate the vertical dimensions – the high scale is always greater than the scale of the situation. In this case, both scales are identical and equal 1:800. On the slopes of the mound one can clearly see the paths leading to the top.

Fig. 1. Model of the Piłsudski Mound obtained in the process of 3D printing in scale of 1:800. Printing time – eight hours, on the slopes of the mound you can see paths leading to the top, the measuring of the 270 points did not provide the smoothness of the model, as indicated by visible edges at the junction of triangles covering the surface

The number of points measured on the surface of the mound (270) proved to be too small to faithfully reproduce its surface, similar to the cone. On the basis of the measured points the triangles are formed, covering the surface. These triangles are clearly visible on the physical model in a form of the edge of the elementary surfaces approximating spatial area (Fig. 1).

For the modeling of the Wanda Mound the Surfer software was used. Using the functions of the program you can get a three-dimensional model of an artificial topographic surface. A regular grid was created (GRID), and as an interpolation algorithm the kriging method was used. The numerical model of the object was reviewed in ArcGIS program and evaluated using the ArcScene module. The model has been exported to *.wrl format and then converted into the *.stl format, using the script created in Python. This procedure may seem to be complicated, but it proves that with the help of widely used GIS software one can create three-dimensional models that can be a batch material for devices printing physical 3D models. The algorithms generating the node points of regular squares grid made the printed model smooth (Fig. 2), even using a relatively small number of source points. The slope surface of the mound shows no edges and irregularities. However, interpolation and smoothing procedure may in this case reduce the degree of accuracy of the real shape of the mound.

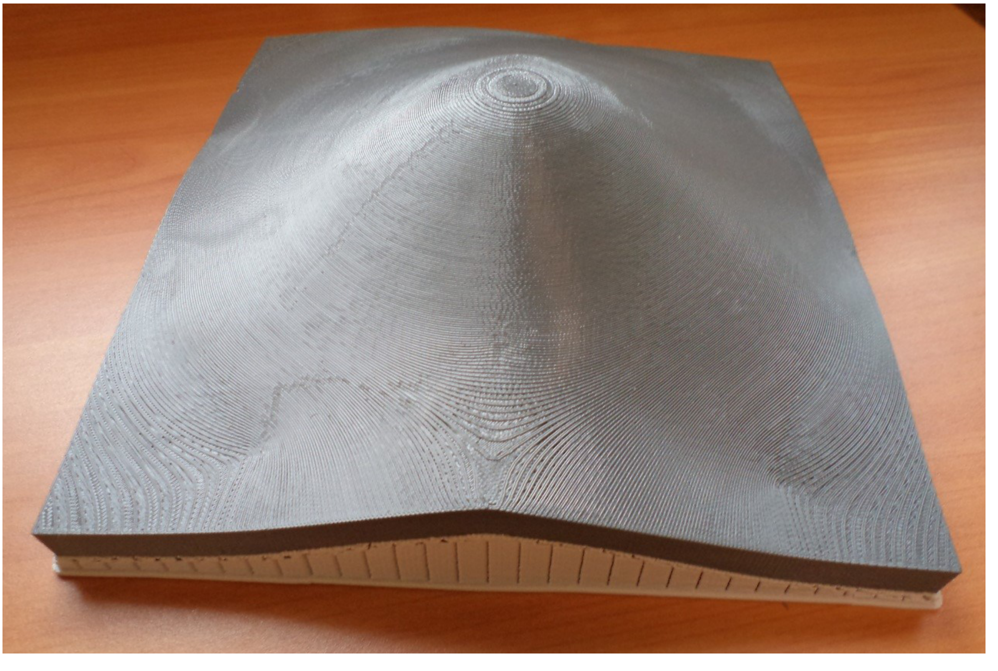

Fig. 2. The Wanda Mound model, scale 1:250. Printing time – five hours, the smooth model, obtained in the process of interpolation and smoothing – due to this procedure it may show some deviations from the real shape

The cloud of the points obtained from the measurement of the Krakus Mound was elaborated using the Leica Cyclone software. The scans from nine stations were connected using characteristic points and targets. Then they were removed from the cloud: two trees growing on the measurement object and the points obtained as a result of an incorrect reflection of the laser beam. Based on the processed points, DTM in the form of TIN was prepared, which was then exported to *.stl format. Such a model allowed for the faithful reproduction of any discontinuities (Fig. 3), what gives to the terrestrial laser scanning method the best possible rating.

Fig. 3. The Krakus Mound model, scale 1:500. Printing time – six hours, the method of laser scanning and of point cloud elaboration provides the high accuracy of reproducing details, on the slope of the mound you can see paths and local elements of micro-lie of the terrain

To create the model of the Kościuszko Mound a cloud of points from an airborne laser scanning was used. Using the software Leica Cyclone the full cloud of points of the fragment of Kraków was cut up to the appropriate size, and the high vegetation located at the object base was removed. Then the network of triangles was created and saved in *.stl format. The ALS-data made possible considering in the model the fort's walls surrounding the mound (Fig. 4). This way one could avoid additional, time-consuming direct measurements.

Technology of airborne laser scanning (ALS) is expensive and not suitable for the measurement of individual objects, but of the larger areas, especially of entire city areas. Currently, such measurements are carried out throughout the country, designed to provide data for the numerical model of land cover.

It can be assumed, that the spatial database will soon be enriched by many objects on which we shall be able to continue these experiments in order to create physical three-dimensional models.

Fig. 4. Model of the Kościuszko Mound, scale 1:800. Printing time – seven hours, high accuracy of reproducing allowed the accurate representation of the path leading to the top and the fort fragments; the thickness of the elementary layer of 3D printing is approximately 0.2 mm

5. Summary and Conclusions

Presently, creative techniques of realistic images using CAD editors are widely used. Such images have many advantages, but there are also some flaws of this method of visualization, which is why there is a need for building physical models of projected objects. The observation of physical models requires no hardware, the model is seen using the principles of everyday experience of the observer – as a realistic three-dimensional object, it can be observed in real time from any site. On the model you can directly determine the spatial relationships between its component parts.

Recently, the application of 3D printing technology – an automatically created physical models technology – is being used very widely.

In this study we discussed the usage of this technology. In order to test the 3D printing technology four Kraków mounds were used as source objects. In this summary we will try to justify the decision of choosing these Kraków mounds as experimental database objects, to evaluate the measurement methods of the source objects shapes and the elaboration of these measurements. At the same time we will try to evaluate the accuracy of the surface reproduction in form of the physical three-dimensional models.

To test the 3D printing technology the following mounds were selected as source objects: Piłsudski Mound, Wanda Mound, Krakus Mound and Kościuszko Mound. The shapes of these objects form compact parts of land surface, they have the hillsides of a greater slope and the line of the biggest fall has the maximum diversified direction. The conical shape of the objects allowed for observing a correlation between the number of points obtained during the measurement and the preservation of a smooth continuity of the reproduced surface. The existing continuity of the surface or the lack of it can be clearly seen on the prepared models. In addition, the mounds have engineering objects (paths and walls) on their slopes – the reproduction of these objects on the model could be additionally tested.

For a comprehensive analysis the source data was obtained by different methods: the first two mounds were measured by the GNSS method, the next mound was measured by a terrestrial scanning, and in the case of the last mound – the source data was obtained from the airborne scanning.

Observation of the Piłsudski Mound model (Fig. 1) shows a lack of smoothness of the mound topographic surface, elementary planes approximating the spatial surface can be observed. This shows that the acquisition of the measured points was too small for an object with a large local curvature of surface.

In the next case, a much smaller number of points was acquired. They have been elaborated by interpolation software, by the kriging method, getting a DTM in the GRID form with RMS-error 0.14 m. As a result of this process, a smooth topographic surface (Fig. 3) was created, at the same time such a procedure reduced the degree of accuracy when compared to the real shape.

Very good results were obtained from the two methods of preparing the models from a cloud of points, using laser scanning. Elaboration of the cloud of points is time-consuming, such source data are however particularly suitable to develop 3D models of irregular shape surface. The models have accurately reproduced shapes, not only of the topography surface, but also the shapes of the engineering objects – the paths leading to the top (Figs 3, 4), or the parts of the fort – in the case of Kościuszko Mound (Fig. 4).

The 3D printing technology can be widely used to materialize the topographic surface and the objects located on it. It can also be used to build architectural models. The models can serve for a number of physical analyses, which are much easier than computer simulations.

Concluding this summary one should also note some flaws of the 3D printing technology. The first is the time-consuming process of the model building. The tested experimental models were built in a time of five to eight hours, using layer thickness of about 0.2 mm. The second flaw is the high cost of creating the models. In this case, the cost of generating the models of mounds ranged from 75 to 140 Euros. These flaws are, however, temporary. The massive development of electronics has led to much lower prices of computer equipment and smaller production costs. A wide development of the 3D printing technology will certainly reduce both – the time-consuming process and the cost of creating models.

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