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Procedural Analysis of the Parameters of 3D Printing Technology in the Process of Manufacturing Objects for Visually Impaired People

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ABSTRACT

Counteracting the social and educational exclusion of visually impaired people is an important issue in the area of knowledge transfer, also in the area of cultural heritage. Visually impaired people get to know the world in an organoleptic way, where the leading cognitive factor is touch. This type of cognitive method cannot be used in museology and historical architecture. Current attempts to solve this problem lead to the use of additive technology understood as 3D printing. The paper presents a modified procedure for obtaining digital 3D models with the use of Autodesk Inventor version 2021, dedicated to creating scalable replicas of architectural objects using additive technology. The applied procedure uses the decomposition of the object into its components and the acquisition of data from terrestrial 3D laser scanning (FARO Focus 3D scanner, Faro Scene software). Printing in the Fused Filament Fabrication technology of a designed minaret representing the architecture of the Timuridian period (minaret of the Ulugh Beg Madrasa in Samarkand, Uzbekistan), originating from the Silk Road area, was carried out due to the size of the facility, divided into several parts. The obtained replica of the minaret was presented to people with simulated pattern dysfunction and a blind person and tested in a pilot test. The obtained results confirmed that the decomposition of the object for the purposes of 3D modelling, the diversified scaling of individual elements to make real 3D replicas of the digital model facilitated the kinesthetic recognition of the relevant architectural object for the respondents.

Keywords: 3D modelling, 3D scanning, 3D printing, cultural heritage, Silk Road, visual impairment

INTRODUCTION

Access to the rich and diverse world of architectural achievements is largely determined by the sense of sight. It is thanks to it that the uniqueness of the surrounding world is discovered: landscapes, views, panoramas, as well as products of human activity – cultural heritage objects that are listed in Article 1 of the Convention of the World Cultural and Natural Heritage [1], in particular monuments, buildings, complexes urban, taking into account their incorporation into landscapes.

Large architectural objects are unrecognisable to people with various types of visual impairment and the degree of damage. Visual impairment can manifest itself in many ways: blurred vision, incomplete vision, fragmented image generation, distorting images, and in extreme cases – the complete loss of visual perception.

The solution to the problem of the possibility of getting to know architectural objects by people with visual impairments is to provide copies of these objects in sizes that will allow such people to fully touch them and "study" their shapes by safe and repeated touching them – the so-called kinesthetic cognition [2–5] (characteristic of infant cognition). Modern technologies of computer graphics: 3D scanning [6], 3D modelling [7] and 3D printing [8] allow for effective collection of data about an object, making a digital 3D model and generating a scaled copy of the original with the use of incremental technology. It is one of the technologies included in the rapid prototyping group. It turns out, however, that in the case of 3D printing of historic architectural objects, there are unexpected problems due to the fact that copies of such objects during 3D replication are proportionally reduced by up to 100–200 times. The obtained replica is characterised by the unrecognisability of small decorative architectural details present in the original building, or their complete loss, and in some cases a deterioration of their structural rigidity. Thus, such copies cannot be used by visually impaired people to get to know architectural objects.

The work concerns:

- modification of the procedure presented in article [9] intended for creating digital models of architectural objects dedicated to 3D printing,
- making a digital 3D model of the minaret from the Silk Road area, selecting the value of the 3D replication process by performing many simulations of this process and 3D printing its copies using the Fused Filament Fabrication (FFF) technology,
- assessment of the usefulness of the made copy for kinesthetic cognition by persons with simulated pattern dysfunction and a blind person.

STUDY BACKGROUND

Visually impaired people exceed 250 million people worldwide and constitute an important potential group visiting the world, practising cultural tourism. This number is constantly growing and sight defects are considered a civilisation disease. In the functioning of such people there are many problems and limitations in everyday life. Problems with sight perception concern not only the perception of everyday objects, but also monuments.

Museums use various technologies to make their exhibitions (exhibits) available, but it turns out that in most cases this information is not available to visually impaired people. This is a problem that in many cases makes it impossible to familiarise oneself with museum exhibits and actual monuments. This problem excludes visually impaired and blind people from the area of exploring cultural heritage [10]. The authors of the work [11] propose a multidisciplinary approach of supplementing the information about historic buildings on museum websites with content for visually impaired people. This will enable the visually impaired to gain a basic understanding of these collections and can certainly help with an actual visit to the museum and facilitate sightseeing. However, the content, descriptions and information of the presented exhibits on the Internet are insufficient for visually impaired people. In addition, studies conducted with the participation of people with visual impairments show that museum websites have a low degree of functionality [12]. Getting to know historic objects for these people is possible only through their touch (kinesthetic cognition) [13]. However, most museums do not allow the exhibits to be touched due to the risk of damage or destruction. In recent years, efforts have been made to enable sightseeing by people with visual impairments. The article [14] conducts research on the behaviour of visitors interacting with replicas of historic museum objects made with additive technology. The research has so far been conducted without the participation of blind people at the Burke Museum of Natural History and Culture in Seattle. For the purposes of the study, copies of four small museum objects were prepared, the size of which did not exceed 15 cm. The obtained results confirm that getting to know the exhibits using the sense of touch is an encouraging and interesting form, and the copies made with the use of additive technology are safe and work well. The City Museum Trier ("Stadtmuseum Trier") [15] has also made attempts to introduce audio tracks, tactile reproductions and replicas for the visually impaired and blind. Study [16] presents the construction of the proprietary device intended for visually impaired people. It consists of three elements: a ring put on a finger, NFC sensors placed on the surface of the printed 3D model (in FFF technology) and an application for a tablet or smartphone. During tactile navigation on the surface of the 3D model, when the finger reaches the hotspot, the ring identifies the NFC tag and activates, via an application, the soundtrack associated with that specific hotspot. In this way, the relevant audio content applies to each hotspot. The authors used scanning, data digitisation and 3D printing to develop the 3D model. The authors of the work [17] emphasise that creating tactile adaptations of artefacts or 3D images is a difficult task, which includes the need for careful surface design, good selection of materials and interaction design that is consistent with the needs and capabilities of the target group. In the work, they present three design explorations aimed at better understanding the ways of interactions. Along with a description of the design research, they present the opinions collected from blind visitors to museums. The authors [18] argue that additive production, if supported by the rescaling of the museum model, can be used to learn about an object through senses other than the visual one. These multi-sensory forms of communing with culture are of great importance for the accessibility of cultural heritage, especially for people with learning difficulties, children, the elderly, blind or partially sighted people. It should be noted that standards for translating 3D objects into multi-sensory perception, which would guarantee optimal information transfer, have not yet been developed – the possibilities of the solutions used should be investigated, tested and codified. Article [19] presents a controlled interactive audio guide based on underwater cameras that act directly only on the surfaces of reliefs printed in the FFF technology. Interactively explored, location-dependent word descriptions provide fast, tactile access to 2.5D spatial information. The authors presented a working prototype, discussed the design decisions and presented the results of the tests carried out with blind users. Article [20] describes the technological process of creating 3D models using the Structure from Motion (SfM) method. It also shows how to overcome the limitations of the automatic digitisation process (correction of the 3D model mesh, textures, etc.), and the method of verifying the compliance of the resulting digital copy of the exhibit with the original. The possibilities of using the created set of 3D models in scientific research, education and popularisation of historical and cultural heritage were also described. The article does not deal with the printing of 3D replicas of digital models.

In [3], the authors used 3D scanning to prepare copies of real digital models for kinaesthetic cognition. Prepared digital models before 3D printing (in FFF technology) were subjected to special treatment, the purpose of which was to increase the depressions and emphasise the protruding elements. Printed models of sculptures and an architectural object were examined with the participation of a blind person. The results of the research indicate the necessity to properly select the scale of 3D models so that the recognition of individual details is possible.

Creating replicas of museum objects, even with complex shapes, using 3D printing technology is possible thanks to the use of 3D scanning and 3D modelling. Technical aspects concerning the use of various scanning techniques for historic museum exhibits were discussed in works [21–23]. 3D scanning using structured light technology was used to scan the statue of Hercules from the Antalya Museum in Turkey and the Khmer head from the Rietberg Museum in Zurich [21]. The paper also presents the issues of selecting 3D scanning techniques for historic museum exhibits in terms of costs, as well as experience and training of staff. Article [22] concerns checking the suitability of stationary and mobile 3D laser scanners for transferring archaeological objects to the digital world. The research confirmed the inability to collect information about the texture, and in the case of a mobile scanner, there was a need for sticking markers, and in the case of a stationary scanner, there was a need to limit the size of artefacts. The authors of work [23], apart from the aforementioned aspects, also deal with the issues of digital reconstruction. Another approach, alternative to 3D scanning technology, is described by the authors of [24]. The article discusses the creation of digital architectural objects through the use of classical 3D modelling. The replicas made with the 3D printing technology were used to get to know the kinesthetic in the board game. The authors of [25], on the basis of the Victoria and Albert Museum in London, also present the possibilities of developing tactile exhibitions. In the light of the literature study shown, it can be seen that the issue of making available objects of tangible cultural heritage is a significant problem and so far has not been properly solved in the technical and organisational aspect. Hence, the authors undertake partial efforts to improve the methods of creating real 3D replicas that can be used to create exhibitions with the option of kinesthetic cognition.

The above articles show that the authors of the kinaesthetic studies used 3D models printed in the FFF technology. In none of the articles discussed above, the authors conducted a survey on a group of visually impaired people. The studies were pilot studies, not quantitative, and thus the results were not presented in the form of graphs and statistical processing.

METHODS

The paper modifies the procedure presented in article [9]. The developed procedure (Fig. 1) allows for the creation of digital 3D models dedicated to making scalable replicas of architectural objects with the use of additive technology. The applied procedure uses in particular: decomposition of the object into its component elements and 3D laser scanning to obtain data about the object. It consists of three main steps (each with additional different activities): (i) an introductory phase; (ii) a decomposition and 3D modelling stage; (iii) 3D printing stage and sharing.

An effective 3D printing simulation process (3a) concerns the selection of printing process parameters, e.g. the type of material, polymer plasticisation temperature, thickness of external walls and the method of filling the object.

INTRODUCTORY STAGE

The choice of an architectural object

Among the many monuments located on the longest land trade route, the Silk Road, one of the architectural structures, the so-called Timuridian architecture – minaret of the Ulugh Beg Madrasa located in Samarkand, Uzbekistan. Data on this object was obtained as part of the second and third Scientific Expeditions to Central Asia carried out by the Lublin University of Technology [26]. The Ulugh Beg Madrasa (Fig. 2a) is the oldest Islamic university which, together with other monuments, forms the monumental Registan complex in Samarkand. It was inscribed on the UNESCO World Heritage List in Uzbekistan. Its construction took only 4 years (1417–1420). It is a great representative of the architecture of the Timuridian period, which combines the traditions and patterns of ancient Central Asian construction. The madrasa, located on the west side of the square has an impressive entrance, a so-called *eyvan* (an architectural element taken from Persian architecture) with two minarets on the sides. The heads of the minarets have numerous and intricate decorations called stalagmites (Fig. 2b). In the 19th century, minarets tilted dangerously and were partially straightened in the 1930s and then maintained in the 1950s and 1970s.

Acquisition of dimensional data

Data in the form of a cloud of points and digital photos were obtained using a 3D laser scanner Faro Focus X330 (Fig. 2a) and a Nikon D5300 camera. The 3D scanner used scanned the surrounding space with a laser and infrared with a system error not exceeding ± 2 mm. In the entire digitisation process, 5 partial scans were performed in positions consistent with the planned layout (about 8 minutes per one scan). The acquisition of photographic data with the use of a camera was carried out in parallel with the operation of the 3D scanner. The data obtained from the scanning process was processed using the Scene software version 2021 to obtain a collective cloud of the object front points. Due to the fact that the 3D modeling concerned only the mimosa on the right side of the pediment of the Ulugh Beg Madrasa, this fragment was digitally cut off from the entire madrasa. As a result, a 3D minaret point cloud was obtained, the file size of which was 0.5 GB. The used Scene software allowed for the dimensioning of individual elements of the object directly on the point cloud (Fig. 3). Plotting the actual dimensions made it possible to determine the values of the diameters and heights of individual parts of the minaret.

Selection of software and tools for 3D modelling

The Autodesk Inventor parametric software, version 2021, was used to make the minaret. Its main advantages include the ability to generate and modify 3D models in terms of its numerical parameters. The Inventor program was used, inter alia, for the reconstruction and modelling of: elements of armor [27], of Betancourt's historical heritage [28]. In the modelling process, a Dell 5540 computer with an Intel (R) Core (TM) i7–9750H processor clocked at 2.6 GHz and 16 GB of RAM and NVIDIA Quadro T1000 graphics card was used.

Selection of 3D printing technology

3D printing technology is based on the implementation of the 3D printing process, which is carried out in an incremental manner. These technologies use different methods of layer-by-layer application of the building material and its selective bonding. Optimisation of 3D printing consists in the selection of technology, equipment and values of adjustable variables of the additive process of creating a 3D model. The most common printing technologies are: Fused Deposition Modelling / Fused Filament Fabrication (FDM/FFF), Stereolithography (SLA), Selective Laser Sintering (SLS). For economic and functional reasons (low weight

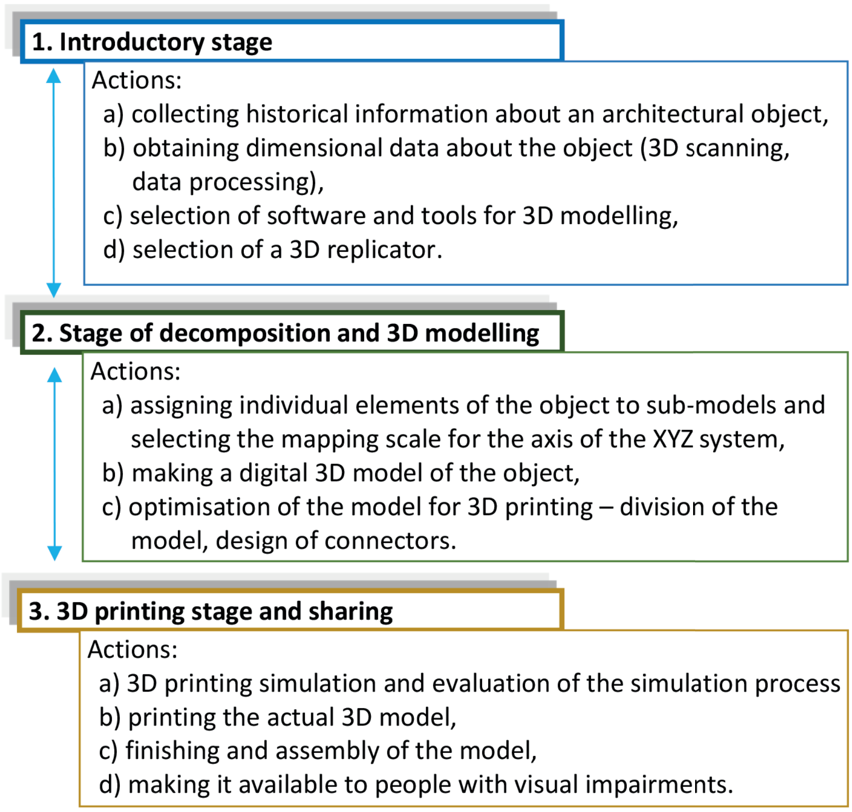

Fig. 1. Procedure for creating digital 3D models dedicated to 3D printing

Fig. 2. View of the Ulugh-Beg Madrasa: a) pediment, b) minaret head

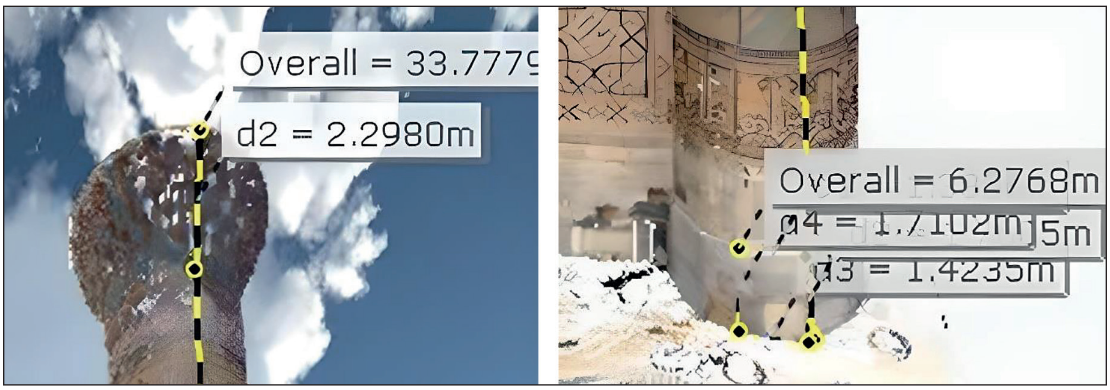

Fig. 3. 3D point cloud of the Ulug-Begh Madrasa Minaret with marked dimensions a) head; b) base

of the printed elements with sufficiently high stiffness), the FFF technology was selected. PLA polymer was used for printing. The choice of printing technology and material was also dictated by the fact that nowadays polymer are used in many research and scientific fields as well as in human life [29].

Creating a real object layer by layer according to a specific shape is realised by saving in the form of G-code in a digital file. The preparation of such a process is related to the determination of appropriate values of the process variables. The first group of variables concerns the speed of the head movements during extruding the material and idle movements. The second group of variables relates to the wall thickness of the printed object, the height of the applied layers and the structure of filling the interior of the object. External walls are printed elements much slower than the filling, hence reducing their thickness, the printing time is reduced by up to several percent. Changing the fill density of the printed model, e.g. from 10% to 20%, significantly extends the printing time, but has a positive effect on its durability. When printing large objects that do not fit into the available printer working space, it is necessary to divide the digital model into appropriate parts.

THE STAGE OF DECOMPOSITION AND 3D MODELLING

The modelled minaret is characterized by parts with a significant amount of small architectural details (head and base of the minaret) and parts without decorations (minaret column). Therefore, the authors of the article decided that the head and base were assigned to a different category of the modelling process than the minaret column. Inspection of the data collected in the process of 3D scanning and photographing revealed that the minaret column is approximately cylindrical and is characterised by a spatial bend, which means that the upper plane of the head is not parallel to the plane on which the base of the minaret stands. In addition, the minaret's column is tapered – its diameter decreases as you approach the head. In the modelling process, the principle "from general to detailed" and the order of modelling from the head, through the column to the base, were applied. Selected stages of 3D modelling of the minaret's head consisting in adding further architectural details forming cylinders of decreasing diameter are shown in Figure 4. This drawing shows the head in a position rotated by 180° in relation to the real system.

In the case of modelling the column part of the minaret, it was decided to adopt a tubular element due to the economic aspects of 3D printing (shortening the printing time and reducing material consumption). The ready-made 3D digital model of the minaret after cutting into fragments, at the stage of adapting to the 3D printing process, is shown in Figure 5. In order to properly assemble the individual elements of the minaret copy, mounting holes were designed in the cut surfaces to form an

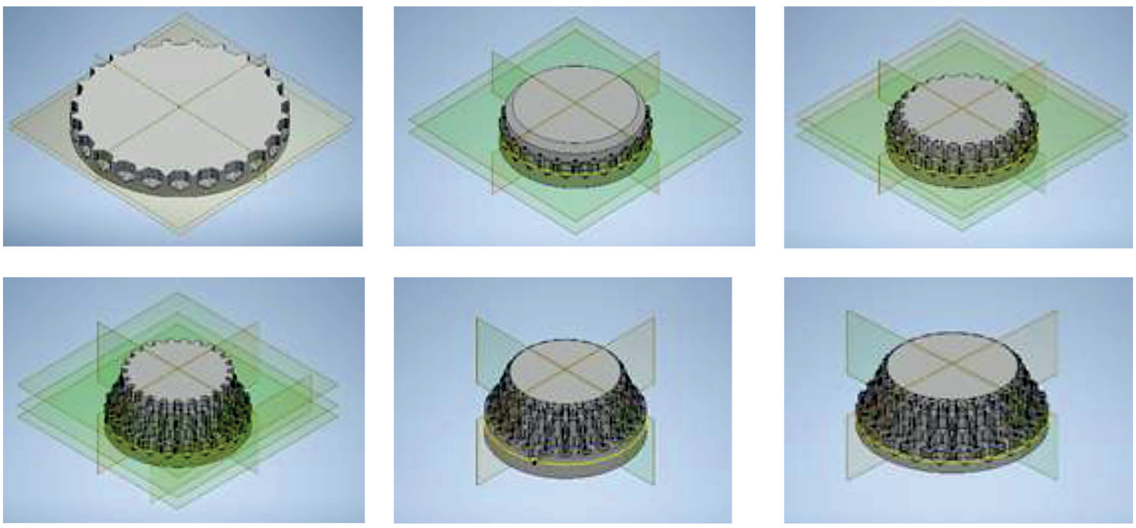

Fig. 4. Stages of 3D modelling the head of the minaret

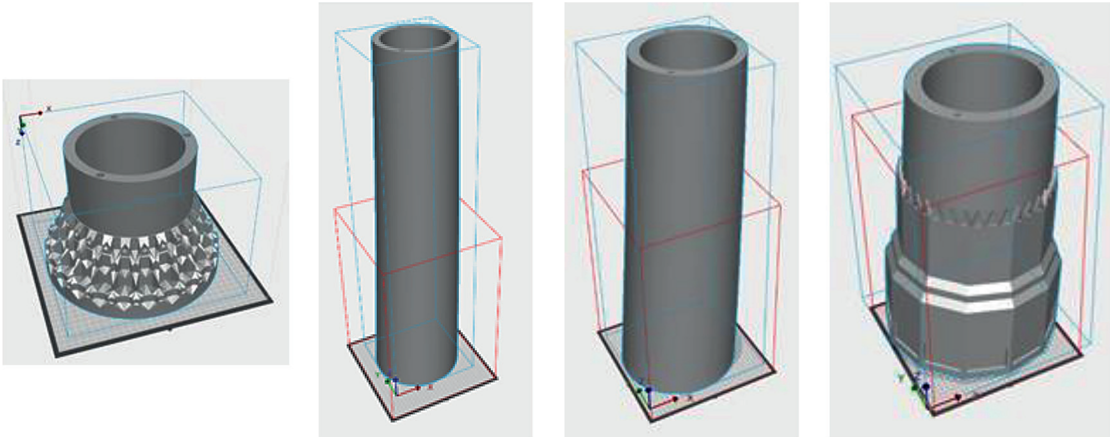

Fig. 5. View of the individual digital elements of the 3D model of the minaret in the Slicer program

isosceles triangle (which guaranteed unambiguous mutual positioning) and pins assembly.

The digital 3D model of the minaret in Inventor is a parametric model, which allows it to be fully scaled without losing details. As a result, there is great flexibility in selecting the size of the printed copies.

3D PRINTING STAGE

3D printing simulations

A specialised Zig-Zag 3D replicator printer working in the FFF technology was used for 3D printing. The working space of the device was: 35×35×45 cm. Before starting to set the values of the replication process variables, simulations of this process were performed for different values of the variables. The following process variables were adopted: wall thickness, interior filling structure, filling density and layer thickness. The entered values of the variables and the obtained simulation times of the printing process of the head with a fragment of the minaret column (Fig. 4) are shown in Table 1–4.

Evaluation of the simulation process

Note that Table 1–4 shows simulation data not for the entire minaret, but only for its upper part, which is about 20–25% of its total. The analysis of the results obtained shows that:

- The relationship between the change in layer height and the printing time is not linear. An increase of approximately 3 fold in the layer height results in less than a 2.5 fold reduction in time, irrespective of the type of structure used.
- Reducing the filling degree of the internal structure from 20 to 15 percent results in an approximately 10% reduction in 3D printing time, irrespective of the type of structure used.
- Increasing the wall thickness slightly increases the amount of material used. 2. A fold increase in thickness results in an approximate 10% increase in material consumption, irrespective of the type of structure used.
- The material consumption is slightly higher for a linear filling structure as compared to a tri-hexagonal filling, which means that the 3D printing time with the use of a linear filling structure is slightly longer.

Table 1. 3D printing process simulation, filling structure: tri-hexagonal, minaret head diameter: 180 mm

Filling	Wall thickness [mm]	1			1,5			2		
	Layer height [mm]	0.1	0.15	0.3	0.1	0.15	0.3	0.1	0.15	0.3
20 %	Printing time [h]	**77.5**	**52**	**32.5**	**77.5**	**55**	**35**	**83**	**58.5**	**35.5**
	Amount of material [g/m]	422/ 142	442/ 149	498/ 167	460/ 154	474/ 159	532/ 179	480/ 161	494/ 166	546/ 183
15 %	Printing time [h]	**68**	**45**	**29.5**	**67.5**	**48**	**32**	**73.5**	**52**	**32.5**
	Amount of material [g/m]	348/ 117	359/ 120	418/ 140	379/ 128	394/ 133	454/ 153	400/ 135	415/ 140	470/ 160

Table 2. 3D printing process simulation, filling structure: linear, minaret head diameter: 180 mm

Filling	Wall thickness [mm]	1			1,5			2		
	Layer height [mm]	0.1	0.15	0.3	0.1	0.15	0.3	0.1	0.15	0.3
20 %	Printing time [h]	**74**	**55**	**33**	**80.5**	**57.5**	**35,5**	**86**	**60.5**	**36**
	Amount of material [g/m]	439/ 148	455/ 153	497/ 167	473/ 158	486/ 164	531/ 179	492/ 166	504/ 169	546/ 183
15 %	Printing time [h]	**63.5**	**48**	**29.5**	**71**	**51**	**32**	**76**	**53.5**	**32.5**
	Amount of material [g/m]	356/ 120	373/ 126	419/ 140	393 / 132	407/ 137	455/ 153	413/ 139	425/ 143	470/ 158

Table 3. 3D printing process simulation, filling structure: tri-hexagonal, minaret head diameter: 90 mm

Filling	Wall thickness [mm]	1			1,5			2		
	Layer height [mm]	0.1	0.15	0.3	0.1	0.15	0.3	0.1	0.15	0.3
20 %	Printing time [h]	**16.5**	**13**	**8.5**	**19**	**14**	**9**	**22**	**15.5**	**9.5**
	Amount of material [g/m]	63/ 21	67/ 23	79/ 27	69/ 24	73/ 25	85/ 29	76/ 26	79/ 27	89/ 30
15 %	Printing time [h]	**15**	**11.5**	**8**	**17.5**	**13**	**8.5**	**20**	**14.5**	**9**
	Amount of material [g/m]	53/ 18	57/ 20	71/ 24	60/ 20	64/ 22	76/ 26	67/ 23	70/ 24	81/ 28

Table 4. 3D printing process simulation, filling structure: linear, minaret head diameter: 90 mm

Filling	Wall thickness [mm]	1			1,5			2		
	Layer height [mm]	0.1	0.15	0.3	0.1	0.15	0.3	0.1	0.15	0.3
20 %	Printing time [h]	**14**	**10.5**	**7**	**16**	**11.5**	**7**	**17**	**12**	**7.5**
	Amount of material [g/m]	66/ 23	70/ 23	80/ 27	74/ 25	77/ 26	87/ 29	78/ 26	81/ 27	90/ 31
15 %	Printing time [h]	**12**	**10**	**6.5**	**14.5**	**10.5**	**6.5**	**16**	**11**	**7**
	Amount of material [g/m]	56/ 19	60/ 21	71/ 24	65/ 22	68/ 23	79/ 27	69/ 24	72/ 24	81/ 28

- Reducing the size of the printed object by 2 times (linear) results in an approximately 5 times reduction in printing time.

3D printing of the minaret

A minaret belongs to the group of slender objects (its diameter is many times smaller in relation to its height). The measurements obtained from the 3D scanning process (Fig. 3a) show that the ratio of the height of the entire minaret to the outer diameter of its head is 14.69. Based on this value, the total height of the printed copy of the minaret can be calculated taking the diameter of its head. Knowing the size and height of the replicator's working space will allow to calculate an initial number of items to be printed. The head diameters were assumed for the calculations as follows: the diameters of the subsequent warheads were to use approximately 75, 50, 25 percent of the replicator's working space, respectively, and the last value of the diameter was to be such that the total height of the minaret copy was slightly less than 100 cm, Table 5.

Printing too large a copy of the minaret for the purpose of kinesthetic cognition by blind people is not an indication, because they would not be able to reach all of its elements with their hands. Finally, it was decided to print the entire minaret with a diameter of 6.5 cm (Table 5) by dividing the 3D model into 4 parts. The printout of the head and base of the minaret, due to the significantly greater number of decorative details, was made with a lower value of the layer height (0.1 mm) than the elements of the columns (0.15 mm). For the purpose of testing the suitability of the copy

Table 5. Summary of the height of the minaret copy and the number of elements after the division

Head diameter [cm]	26	18	9	6.5
Total height of the minaret [cm]	381	264	132	95
Number of elements to be printed	9	7	3	3

for the needs of blind people, prints of the minaret's head were also made for the following values of its diameter: 26 cm (blue), 18 cm (orange), 9 cm and 8.7 cm (black), as well as the base of the minaret with a diameter of 10 cm head, which gave the base size equal to 12.5 cm (orange). The layer height of 0.3 mm was used for the diameters: 26 cm and 18 cm, and for the others – 0.15. A tri-hexagonal structure with 15% filling and a wall thickness of 1.5 mm was selected for printing. The minaret heads were printed in an inverted position (Fig. 5) to avoid the generation of supports by the Slicer program.

Examination of the object by the blind

The pilot studies were carried out in two stages: the first stage on people with simulated visual impairment, and in the second stage – with the participation of a person who was completely blind from birth.

Stage 1. The pilot studies were carried out on a 5-person group (1 woman and 4 men aged 30–50) with simulated sight dysfunction, which means that during the study healthy people were completely blindfolded. The research was carried out in the 'Lab 3D' laboratory of the Department of Computer Science, Lublin University of Technology, in accordance with the principles of research ethics. People were led into the room, sat at the table, covered their eyes, and then the researcher placed the printed objects on the table (Fig. 6–8). Objects were shared in a random order, and subjects were asked to comment out loud on their feelings so that research notes could be kept. The people were informed that these would be parts of the minaret. The conducted pilot studies were qualitative studies. The aim of the research was:

- checking the possibility of identifying the exhibit,
- assessment of the correctness of the size of the 3D copy of the object with regard to the number of details,
- assessment of the suitability and properties of the material used for 3D printing.

The research was carried out according to the following scheme:

- study participants were asked to try to classify the object into an appropriate group (e.g. head, column, base) and to identify individual details of the touched object.
- the participants were to test the perceptibility of the decorative elements on the head and base of the minaret under the fingers,
- participants tested the surface roughness of individual elements of the minaret copy due to the use of different layer heights in the process of additive creation.
- participants were to comment on the suitability of the material used for 3D printing.
- the participants were asked to assemble the minaret.

Stage 2. The research was carried out in the home of a blind person (age group 65+) who agreed to disclose his/her image. The objectives of the research remained unchanged. The

Fig. 6. The process of examining the head of the minaret

Fig. 7. The process of examining the base of the minaret

Fig. 8. The process of assembling the minaret

respondent was informed generally about the nature of the examined object. The person touched the models served one by one and commented their feelings aloud while exploring them. The research began with 3D models of the minaret head printed in various sizes, followed by the base of the minaret, and models of the minaret columns. At the end of the research, they were asked to put the minaret together, which was done (Fig. 9).

CONCLUSIONS

The process of making a real 3D copy with the use of 3D replicators requires a preparatory process and then optimisation of the printing process. Contrary to the information commonly reported on the Internet, the time of 3D printing a single element of an architectural object may take many hours or days. In the light of the work carried out on the 3D modelling process, 3D printing simulation and testing the suitability of real 3D copies for the blind, the following conclusions can be drawn:

1. Persons with simulated pattern dysfunction:

- The participants of the research easily recognized the individual components of the minaret, regardless of their actual size. Certain doubts arose only when distinguishing the minaret column from the minaret base for prints with small diameter elements.
- The participants agreed that the recognisability of architectural details occurred only when touching the head printed in large sizes

Fig. 9. Examination of the elements of 3D models of the minaret with the participation of a blind person

(diameter 26 and 18 cm). Details on the base were noticeable in the larger of the prints (orange print, diameter 12 cm).

- The participants agreed that the smoothness of the copy material of the object was sufficient (printout with a layer height of 0.3 mm). They emphasised that the lightness of the elements is a big advantage because it is easy to manipulate.
- The assembly of the minaret turned out to be too difficult for most of the respondents. Only one person completely coped with this task (Fig. 8).

2. A blind person:

- Only in the case of the smallest sizes of the minaret's head, the perceptibility of shapes was too weak.
- The respondent was able to calculate the number of layers of details decorating the head (compare Fig. 4).
- The smoothness of the details of the head, base and columns was satisfactory regardless of the size of the 3D model tested.
- The respondent expressed his satisfaction with the lightness of the models, which allowed for their free manipulation and kinaesthetic learning while holding them in their hands.

The results obtained from the study of a blind person generally confirmed the results obtained from the group of people with simulated sight dysfunction. The obtained results show that when preparing copies of architectural objects for blind people, it should be a good practice to print elements with a large number of details as separate objects on a larger scale, so that these details can be recognised in kinesthetic cognition.

Future works

The authors are convinced that in future works it will be possible to develop procedures in the AutoLisp language, which will significantly facilitate the definition of the scale of individual decorative and architectural elements and will contribute to the acceleration of the modelling process and optimisation of the appearance of the final printed copy. The authors also plan to create Braille inscriptions on the surfaces of digital 3D models and print them.

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