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Digital craftsmanship for education and diffusion of scientific culture: the model of herringbone masonry in a circular dome

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Digital craftsmanship for education and diffusion of scientific culture: the model of herringbone masonry in a circular dome

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Abstract. In this paper the experience is reported of the use of 3D printing for the dissemination of a cultural content. When Filippo Brunelleschi vaulted the dome of Santa Maria del Fiore in Florence without using any scaffolding, demonstrated the ability to control the constructive process in its structural essence. The comprehension of the static principles that stand at the base of the equilibrium of a circular dome are necessary to understand the work of the architect and the reason of the herringbone brickwork adopted. These principles can be easily explained, also to people who do not have any technical education, by means of a three dimensional model. A wood model realized by hand in the '80 was reproduced in a smaller scale with 3D printing. The geometry of the model was easily reproduced with a parametric modelling software and was then elaborated to produce the geometric models for sintering polyamide voussoirs. A comparison is attempted between the cost of the two physical models in term of work time and print time, and a balance is made to highlight the value added to the production of such didactical models by the 3D printing process.

1. Introduction

In the last years a quick development of digital technologies has addressed image analysis and computer aided design. The use of images since the seventies had seemed alien to the digital era; on the contrary, later, graphical computational methods and iconic interfaces were recovered, and media directed to processing and reproducing sounds and images, spreading what is called virtual reality. Virtual image and animation reached very high quality levels, allowing to create special effects used in cinema and animation works. New generations have grown playing with computer games and multimedia tools that represent, also, powerful learning transfers and cultural amplifiers; however, they have often lost contact with matter and with physical play and have therefore impoverished their store of experience. They need, now more than ever, to touch with hand the physical phenomenon and bring it again at the center of the sensory universe, rather than reduce it to the mere visual representation. Once again, the tools that can contribute to solve this anemia may be found in the digital technologies themselves, that are quickly spreading across the territory of other senses. In fact, the digital design phase originally introduced to assist the design process, planning, calculating and simulating complex objects, has proved to be a mean to rapidly create physical models and prototypes, and has radically changed the manufacturing industry due to new digital fabrication methods. The underlying principle that all additive manufacturing methods have in common is that solids are generated automatically on the basis of a digital 3D model by adding numerous small (compared to the size of the solid) units of material. Therefore, there are no specialized tools necessary to fabricate differently shaped objects, which makes additive manufacturing particularly economic where single parts and small batches are to be produced. In addition, additive manufacturing allows a high degree of geometric freedom and offers the opportunity to form parts, that are otherwise difficult to produce, or



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only with great effort. Additive manufacturing includes incremental additions of materials in designated locations. The traditional manufacturing processes place many constraints on product design; on the contrary the flexibility of these technologies allows us to optimize design for rapid production, which by its nature eliminates waste [1][2][3][4]. For each technology the process of fabricating layers, printing ink and power source are different, based on different materials and their characteristics. Additive manufacturing has become an integral part of modern product development and 3D printers are currently affordable for several fields of use [5][6][7].

Fab-labs have developed and the term “digital craftsmanship” has quickly spread to describe the relation between the worker and the product both from the point of view of the number of the produced pieces and for the total control of the process is comparable to traditional craftsmanship.

In this paper a case study is presented in which the computer graphical tools and the 3D printing have proved to be an effective system to realize a didactical model that represents the building technique and the static principle of the Dome of the Florentine Cathedral. These two aspects are necessarily tied and represent the recipe that permitted to build the Dome without any scaffolding; the comprehension of the static principle that underlies a circular dome is simply stated by the evidence of a physical model and represents a step absolutely necessary to understand the contribution of Filippo Brunelleschi to the development of the Renaissance architecture.

In section 2 the geometry of the Brunelleschi’s Dome is briefly described, and the realization of a simplified circular wood model made by hand in the eighties with the supervision of Salvatore Di Pasquale is recalled. In section 3 the generation of the numerical simplified model for the 3D printer in polyester is described. Finally, an evaluation is attempted of the advantages of the new technique that can be in this case defined as a digital craftsmanship.

2. The geometry of the Dome of Santa Maria del Fiore Cathedral

In 1977 the international congress held for the 6th century from the birth of Filippo Brunelleschi [8] offered to several researchers that dealt with the work of Brunelleschi, the opportunity to meet and to discuss. In particular, the substantial agreement of the works of Salvatore Di Pasquale and of Rowland J. Mainstone [9][10] permitted to give the first explanation in modern language of the static principles at the basis of the realization of the Dome of Florentine Cathedral. Since then, many researchers had added useful contributions to the study of the history of the “Cupolone” (“Great Dome” as the Florentine people calls it) [11][12] but the basic principles of the building technique that permitted to Filippo Brunelleschi to complete the building of the largest masonry dome in the world without using any scaffolding, were formerly described by these two scientists and have been later commonly accepted.

The scheme that describes the geometry of the profile in correspondence of the external ribs is reported in figure 1 and is similar to the famous drawing by Giovanni di Gherardo da Prato (1426); it is in agreement with the detailed description reported by Manetti [13] (A. Manetti, “Vita di Filippo Brunelleschi preceduta da La novella del Grasso”) and successively transcribed by the main researchers. The internal profile (figure 1) is described by a circle which center corresponds to $1/5$ of the internal diameter; the external profile is described by a circle having the same center that, in this case, corresponds to $1/4$ of the external diameter. Apparently, the dome is a cloister vault obtained by crossing of four barrel ogival vaults which axes incident angle is 45 degrees: the open space within the vault is the intersection of the space within the four barrel vaults (while the open space within the groin vault is the union of the space within the barrel vaults).

Indeed, the internal structure of the dome is that of a solid of revolution, that is the bricks have been layered according to the surface of cones as usually is for circular domes. This confers to the dome internal continuity and produces the ability to better distribute the internal stresses. Even better, the herringbone pattern of bricks would not be effective for vaulting the dome without any scaffolding if the dome was not a circular one. Circular domes are said to be formed by arches and rings; every ring, once completed, is self-supporting; some sort of centering is necessary only till a ring is completed. But the Dome of Santa Maria del Fiore was so large that no one had ever seen. The herringbone disposition of bricks is useful, in this extent, to divide the very wide rings of the dome in smaller sectors.

The exceptional nature of Brunelleschi's work lies in the ability to control the constructive process in its structural essence and to produce an extremely innovative solution of a problem in which neither mathematical instruments nor physical models could guarantee the exactness. It is not possible to fully understand the work of Filippo Brunelleschi, even from the point of view of the art historians, neglecting his expertise in the static of structures, proved by his determination in making decisions about facts in which small errors could produce huge catastrophic consequences.

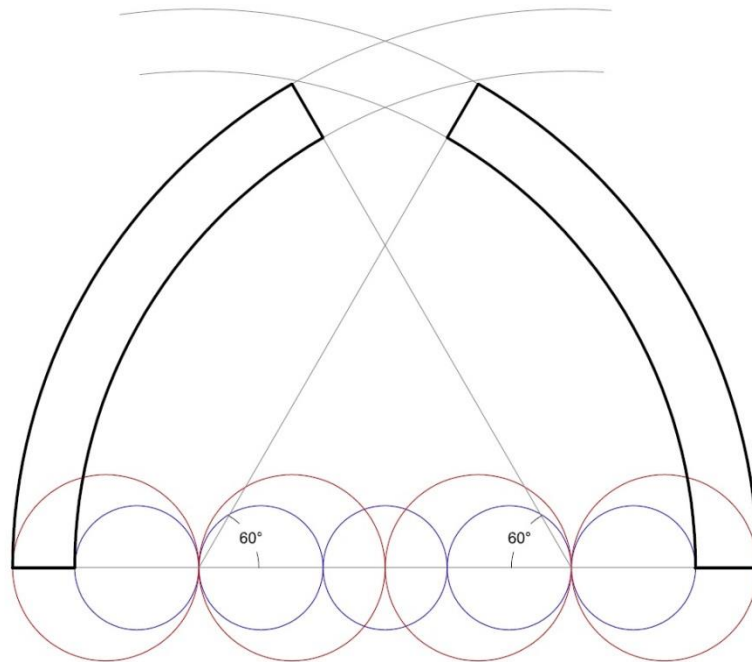


Figure 1. Scheme of the proportion of the dome, in correspondence of the ribs.

3. Early wood didactical model

In the years between 1977 and 1790, the dissemination of the new understanding about the Dome of the Florentine Cathedral was one of the main interests of Salvatore Di Pasquale. Together with new studies about the work of Brunelleschi, a great deal of models were realized in these years, with the help of graduating students. This great season of research led also to the collaboration with the Institute and Museum of History of Science, on the occasion of two international exhibitions: *Prima di Leonardo. Cultura delle macchine a Siena nel Rinascimento* [14] (Siena 09.06.1991 - 30.09.1991) and *Avignone 20.06.1992 - 27.09.1992*) and *Gli ingegneri del Rinascimento. Da Brunelleschi a Leonardo da Vinci* [15] (Parigi, Firenze, New York, Londra, Tokio, Taranto, Pechino, Wuhan, San José, Tunisi, from 1995 to 2011).

In particular the wood model represented in figure 2 was realized with the aim of explaining the static principle and the efficacy of herringbone technique to young students. The model describes a circular dome with the same proportion of the arches that correspond to the edges of the octagonal dome, and the function of the vertical voussoirs as support of the bricks of the ring is intuitive.

The wood model is about one meter wide and was realized by hand, cutting wood. The concept of this model was pointed out by Salvatore Di Pasquale with Aldo Regoli, at that time technician that worked for the Official Laboratory for Material and Structures Tests of the Department of Construction of the University of Florence. It is hard to make now an evaluation of the time needed for the realization of the wood model, but we can argue that the work absorbed about 140 hours, excluded the time necessary for the design process.

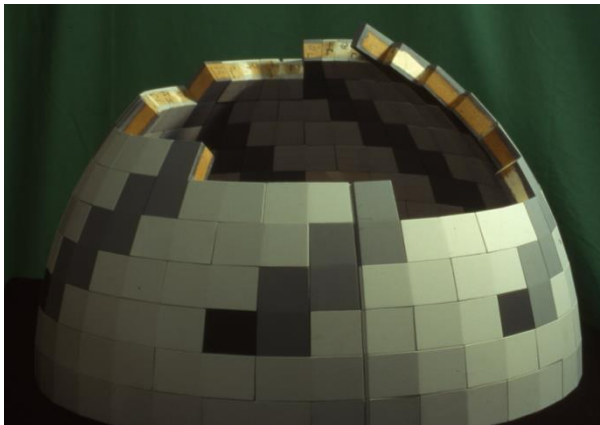
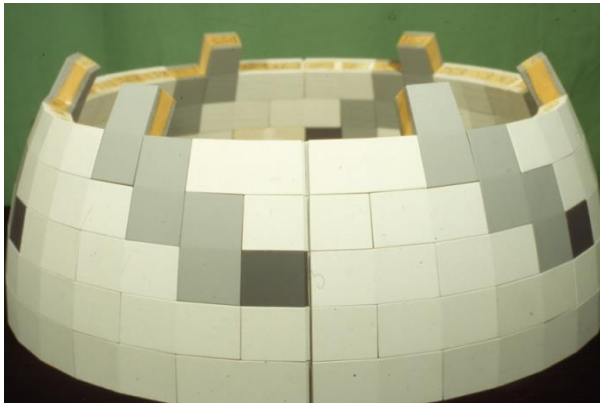
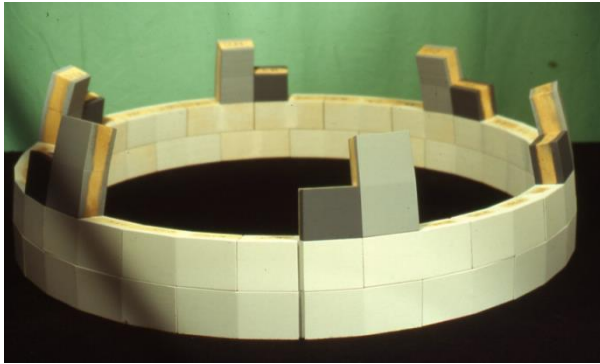


Figure 2. Photos of the early wood model.

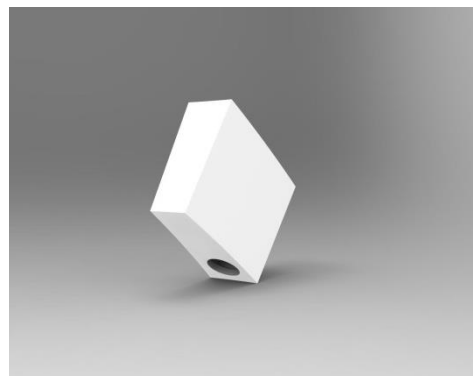
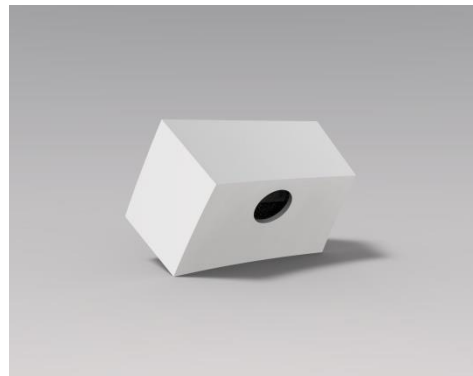
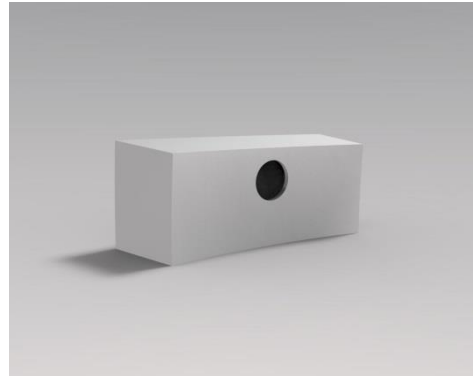


Figure 3. Digital representation of the 3D model and three of the voissours.

4. 3D printing for the realization of the sintering didactical model.

After around 30 years the wooden model had been seen by hundreds of people: visitors of small exhibitions organized by the University of Florence, students of the Faculty of Architecture, students coming from various high schools or even elementary schools on the occasion of lessons prepared for them, and also visiting professors that occasionally came to hold lessons and workshops at the Department of Construction. The need has been felt to repair the old model and, at the same time, to realize a new one with modern technologies, that could also be more apt to the transportation.

The decision was taken to reproduce the physical model with a 3D digital technique, produced with a parametric design software. The design process, once known the geometrical genesis, is quite simple. As the previous wooden model, the digital model was obtained starting from the ideal proportions reported in figure 1 and related to the edges of the real octagonal Florentine dome, drawing two

concentric circular arcs pointed in one fifth of the internal diameter and one fourth of the external one, and subtending at the center an angle of 60 degrees. The region comprised between the internal and external arcs and the two radial line segments that joint their endpoints was then extruded rotating 360 degrees around the vertical axe of the pointed arch, to define the volume of the circular dome. This has the same proportions of the Dome of Santa Maria del Fiore but has a circular base and is able to convey the static principles that make the herringbone effective in a circular dome.

The model was then “cut” into 11 rings according to the cones on which the mortar bed joints of the real structure lay, and then into 204 voissours in all, according to the old wooden model. The number of voissours was recognized to be effective to meet the necessities of convey the message and of maintaining the model sufficiently handy and portable. The different elements (21) were then isolated and intended for the 3D printing in polyamide.

The printing technique used is the Selective Laser Sintering (3D SLS) that is a powder-based 3D printing technology. As in all 3D printing techniques, the object is produced through an additive process in which layers of material are superimposed and the printing process starts with a computer-aided design (CAD) file converted to .STL format, which can be read by the printing apparatus. Specifically, in the SLS technique there is a selective fusion of material in a granular bed, usually polyamide powder dispersed in a thin layer on top of the build platform inside an SLS machine. Normally a laser is used to sinter the medium and form the solid, directing the beam to the specific point to be hardened, through a system of directable mirrors. If the beam is powerful enough, it is also possible to use metal powders. Once a layer is formed, the platform of the SLS machine drops exposing a new layer of powder for the laser to trace and fuse. This process continues until the entire object has been completed. In this variation, the unmelted medium serves to support the protrusions and thin elements in the part being produced, reducing the need for temporary auxiliary supports for the workpiece. Such supports are often necessary with other 3D printing methods (stereolithography or fused deposition modelling) making them more time-consuming than SLS. This printing technique permitted a good control of the geometry and accuracy in the planarity of surfaces.

The elements that compose the wooden dome and the printed dome are shaped differently. The wooden model necessarily appears faceted, in fact it would have been laborious to craft each piece manually in order to make it curved, on the contrary with the 3d print, it was possible to create curved elements.

The final dimension for printing was decided as a compromise between the necessity of transporting the model and assembling it, and was 45 cm in diameter, about a half of the old wooden model.

The voissours (figure 3) were given a hollow shape to reduce the printing time and the possible consequences of shrinkage, and to provide for possible filling with heavy material. The small scale employed and the low mass density of polyamide in fact produced very lightweight blocks (the whole dome is less than 1 kg) which mass can be in this way easily increased.

Also, the external surfaces of voissours can be colored to highlight the role of horizontal and vertical blocks (figure 4).

The 3D printing was executed by Kentstrapper Srl in Florence. The total time necessary for the production of the digital 3D model was about 24 hours; also the time necessary for the printing and the post curing can be evaluated in about 24 hours.

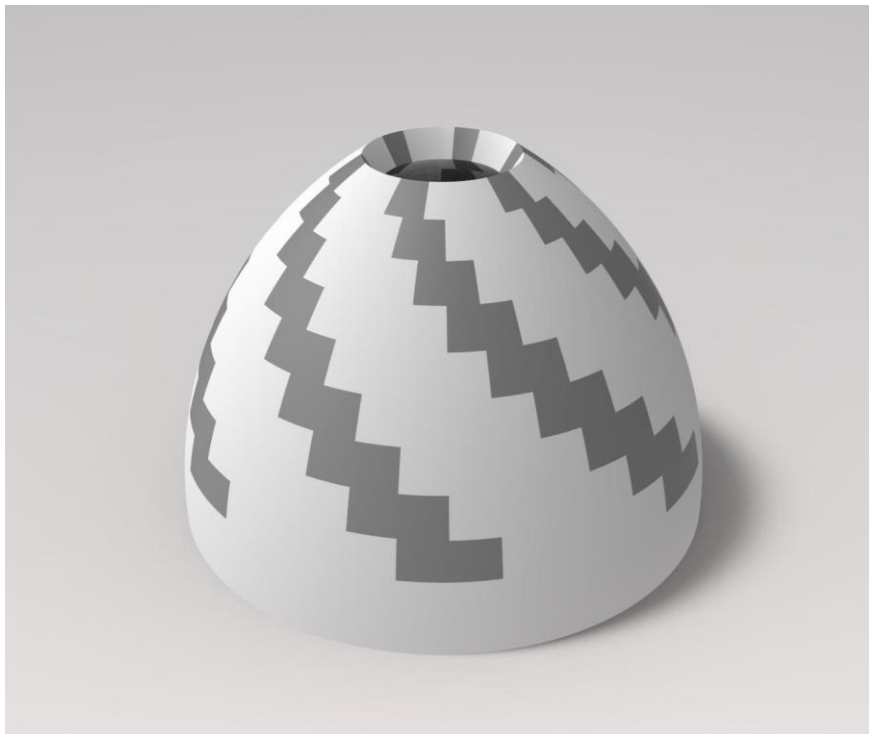


Figure 4. 3D model

5. Conclusions

A physical model was described, intended for didactical use, that explains the static principle of a circular dome and that is useful to understand the effectiveness of the herringbone brick pattern and the contribution of Filippo Brunelleschi to the vaulting of the Dome of Santa Maria del Fiore. This is the faithful reproduction of an earlier wood model realized in the eighties by Aldo Regoli for Prof. Salvatore Di Pasquale and the comparison of the two models, identical in geometry and proportion but different in materials and manufacturing method, gives now the opportunity to think of advantages and disadvantages of the two techniques.

The production process of the printed model can be addressed as a digital craftsmanship as one single person or a small staff is able to control the whole process from design to production. The plastic model is exceptionally precise in geometry and the external surface looks smooth while the wooden model is necessarily faceted; moreover, it can be easily transported as it is very light. As a con we must admit that it is quite fragile, and the lightweight makes it less stable when mounted. Most interestingly we can compare the production process: the wood model is the work of a particularly skilled artisan who spent time in the design process and, most of all, in the production of a single piece; the production of a second model should have absorbed the double of the production time. On the contrary, 3D printing is competitive from the point of view of the production time, and is competitive with an industrial production in case of small number of replicas. In this specific case we can assert that the use of new technologies add value to the process as they permit to produce the didactical model with a very low “cost”. Moreover, the graphical model necessary for the production can be transferred via web and, due to the wide diffusion of fab-lab, permits a 0 kilometer production also in geographical areas usually thought of as marginal and isolated. New technologies in this case are able to improve accessibility to cultural contents.

Making an attempt of cost-benefits analysis, on the weighing plate of costs we should consider the roughly 24 hours for the production of the digital design and 24 hours for the printing and curing of the plastic model; on the weighing plate of the benefits we have to consider a life time of

approximately 10 years and a fruition rate that can be calculated taking as a reference the about 500 students that had the opportunity to observe the model in its first two years of life. In this balance the knowledge necessary to imagine this object as well as the effective knowledge produced on attenders is not easily evaluable.

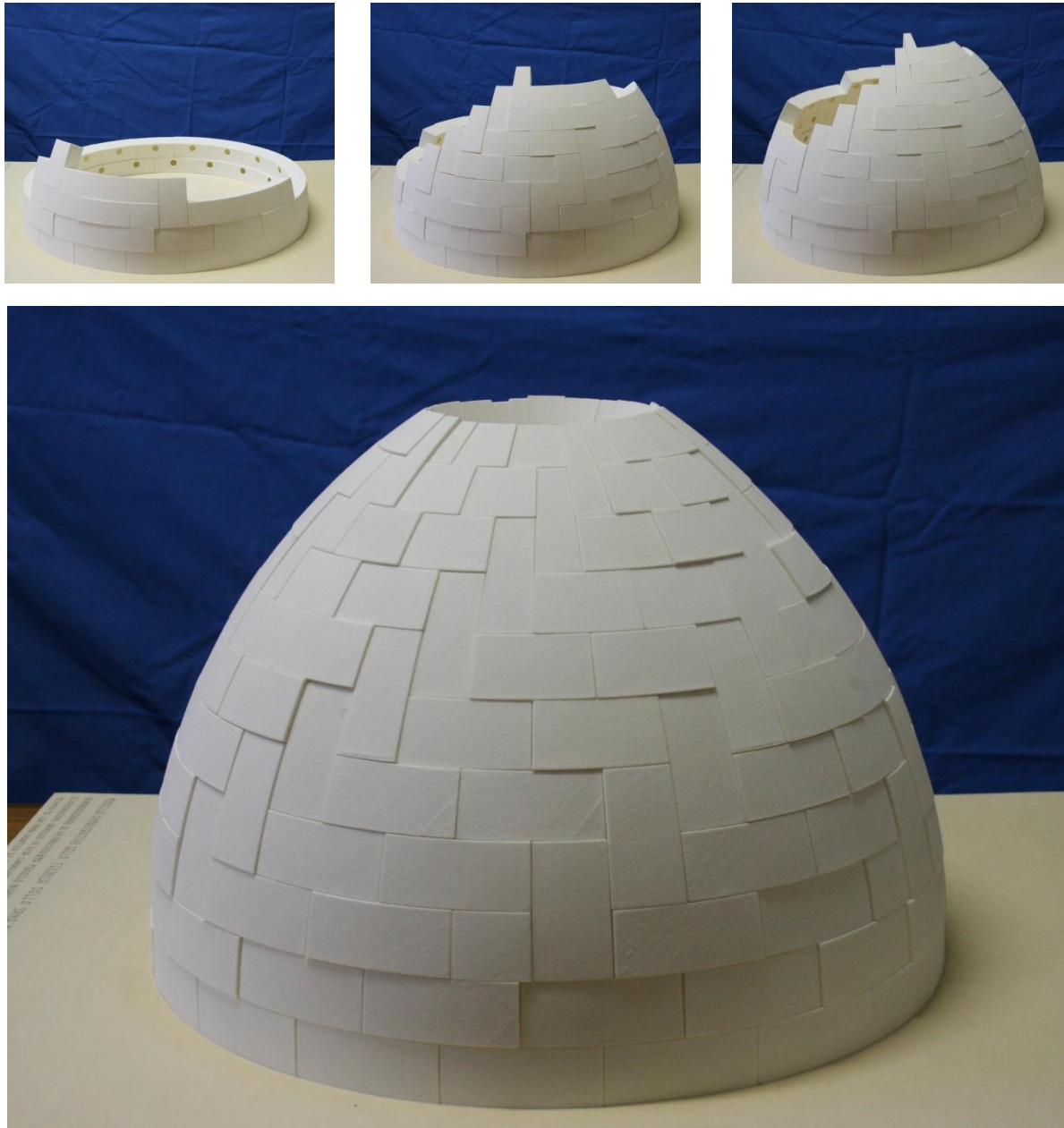


Figure 5. 3D printed model

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