Direct Digital Manufacturing: A Challenge to the Artistic Glass Production

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1 Introduction

Currently the high hand-labor costs, long production times, lack of automation and high energy consumption associated with the high temperatures required to produce pieces of glass, are identified as the main inhibitors of growth and economic development of the decorative and utility glass industrial sector. Current production processes impose limitations on the complexity of the geometry and shape of the glass pieces to be produced, which in turn greatly restricts the creativity of designers and consequently, the characteristics of differentiation and innovation presented by new products on the market.

Additive Manufacturing (AM) technology allows the rapid, automated and fully flexible manufacturing of products from templates generated by CAD (Computer Aided Design) in a fast, automated and fully flexible manner. Compared with the classical manufacturing process for artistic glass parts, the AM requires a low volume of material, and offers the potential of higher speeds, greater quality and

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lower cost of production. Furthermore, the absence of tools translates into an almost total freedom in the generation of complex geometries, which offers a versatility which is non-existent with current productive systems. AM is also associated with the absence of waste material regardless of any complex shape, material or additive technique. This allows designers to create physical forms of immeasurable complexity from the generation and optimization of three-dimensional digital models (3D) [1–3].

The core of this work is focused on direct digital additive manufacturing of glass components. This requires a comprehensive methodology that integrates several approaches to glass additive manufacturing with design, control, management, information, as well as the networked communication intrinsic to the developments associated with the industrial revolution 4.0. Thus, the global purposes of this work consider the design and development of innovative equipment with a "*hand-made*" stamp as it includes a haptic interface where the artisan and/or the designer can create their pieces directly using their hands, i.e. without using a computational drawing tool. Through the use of appropriate computational tools, this piece will be converted into a digital representation that can be used subsequently by the additive manufacturing equipment to produce quickly and automatically the hand designed piece. Alternatively, the pieces to be produced may have also originated from any computational design tool commercially available.

In short, the equipment includes a trajectory generator composed of a set of four or more axes (x, y, z, ω or more), which are monitored and controlled by software. The system contains three interfaces: (i) a haptic interface, where the craftsman and/or designer may create a piece by hand but which generates a digital

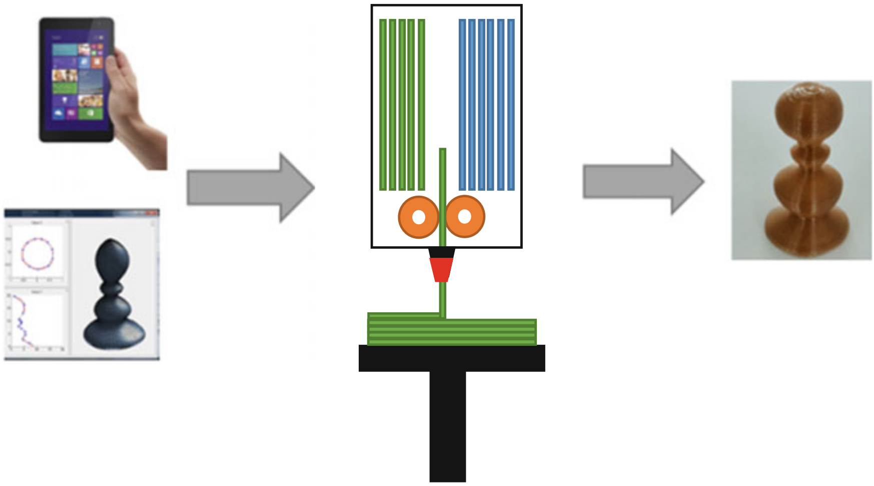


Fig. 1 Illustration of the global direct digital additive manufacturing equipment for 3D glass parts printing

representation which will subsequently be used by the additive manufacturing equipment to produce quickly and automatically the part designed by hand; (ii) a connection interface to the operator, and (iii) other communication with external systems. These are outlined in summary form in Fig. 1.

2 Evolution of the Decorative and Utilitarian Glass Industry in Portugal

Although the glass industry was introduced into Portugal in the second half of the fifteenth century with the founding of a small factory in the town of San Pedro of Vila-Chã, it came to Marinha Grande in 1745, as a result of the transfer of the Royal Glass Factory of Coina by King João. The abundance of the essential raw materials in the region prompted the development of a glass industry in the Marinha Grande region where, currently the glass industry remains active. As a result of the 1755 earthquake in Portugal, there was a great demand for glass due to the need to reconstruct the City of Lisbon. With the support of the Marques of Pombal, in 1769 King José I granted the Stephens brothers, founders of the Royal Navy of the Great Glass Factory, the power to use the wood of the Leiria pine forest to feed the large furnaces, making Marinha Grande the most important center of glass making in Portugal. This led to an significant increase in the number of companies operating in the glass industry in the nineteenth century [4]. Consequent to this expansion, other core businesses developed in Marinha Grande as is exemplified by the moulds industry that is today recognized worldwide for the quality of the products, export-oriented, technological modernization, skilled labor and production flexibility.

In the middle of the twentieth century the container/vessels glass sector, was greatly automated. In contrast, the artistic and utility glass sector witnessed continued stagnation as a lot of handwork, sometimes unskilled, is still needed. In addition, the glass sector has been associated with high energy consumption because of the very high manufacturing temperatures. As a result, the final product has a high commercial value. This strangles the economic growth of companies which have seen a drastic reduction in their profit margins. Reducing costs is seen as the only way to compete in the global market. Moreover, in recent decades we have witnessed an unprecedented invasion of Western markets with products from the countries of Eastern Europe and Asia, where the hand labour and energy costs are lower and this represents a threat to the global economic system.

The production of decorative glass pieces with more complex three dimensional shapes using conventional thermoforming processes, e.g. molding, slumping, fusing, forming, sintering and blowing, also require the production of complex molds, which are difficult to obtain, and this represents a serious obstacle to designers in creating different parts, besides the high costs and times associated with the process of development of new products.

As a consequence of poor economic growth and the absence of innovative business strategies, aspects such as quality, innovation, and design were compromised. This condemns continues to condemn, in the medium term, the survival of traditional companies producing utility and decoration glasses in Portugal. In addition, the disappearance of the artistic glass manufacturing sector compromises the survival of other companies that are involved in the life cycle of such glass products. There is an urgent need to promote within the glass industry the concepts of innovation and technological development so that companies start to compete with their own brands that meet the quality requirements and technical accuracy imposed by the different national markets, and fundamentally the international ones. This work arises in the context to draw together tradition and innovation for the economic strengthening of a potentially productive sector—the glass artistic and utility industry. This industry was the genesis of the major industrial clusters in the Leiria region and hence is of immeasurable historical and cultural importance. It is expected that the implementation of the proposed AM system results in the mass production of pieces in glass, clear or multicolor, without creative boundaries which will lead to the differentiation and affirmation of this glass sector at the regional—Marinha Grande—national and international levels. The new equipment will undoubtedly contribute to the survival of this sector, as well as to its expansion making it more competitive as it meets the demands of today's markets.

3 Glass Additive Manufacturing Technology

To meet the market demands with regard to price, quality and delivery times, it became necessary to resort to the production of models and prototypes that can be used to assess the functional and aesthetic value of the products. AM has, in this respect, an important, powerful and revolutionary role. Since the appearance of the first additive manufacturing systems, research and the search for new applications has not stopped. In fact all industries that develop and produce components and products should use this technology due to the high production speed, creativity, efficiency, affordability, low production cost, environmental sustainability, design optimization and reduced costs that characterize it [1, 2]. In addition, AM technology opens new paths for innovation and offers a range of logistical, economic and technical advantages [1, 3].

AM includes a number of technological processes that enable making three-dimensional (3D) physical models layer-by-layer directly from a digital definition as described in Ref. [5]. These processes can be used for the production of components on any scale from microscopic objects to large objects. AM technologies can be subdivided according to the type of process and materials involved as well as the functional purposes of each one of the manufactured parts [1, 5]. Notwithstanding different objectives, Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Fused Deposition Modeling (FDM) and 3D printing (3DP) are the most commonly processes with glass AM [5–16]. The SLS and SLM processes were used to work soda-lime glasses, quartz and borosilicate [6–10]. The glass objects printed by these sintering processes are extremely brittle and with an opaque appearance due to light scattering from glass powders caused by incomplete densification [9, 13–16]. The latest SLS experiments with glass, attest to the opacity of the products and their poor mechanical properties. The internal porosity of the parts produced leads to dispersion of light, thereby limiting transparency in the application of this technique [10]. The FDM technique allows for 3D objects with good mechanical, durable and fully functional properties. The 3D object is built layer by layer by the addition of polymeric filaments which are melted and extruded through a nozzle that moves in the x-y plane [11]. The major drawback of this process is the need of structural supports during manufacturing. These supports are made simultaneously with the part to be built using a less resistant material, e.g. a wax or water-soluble polymer [17]. The FDM technique has been used to obtain translucent ABS parts and to extrude bone scaffolds from bioactive glass [11, 12].

Based on extrusion techniques, an AM glass-printing process called G3DP (Glass 3D Printing) has been developed by researchers in the Mediated Matter Group at the Massachusetts Institute of Technology (MIT) Media Lab in collaboration with the Glass Lab at MIT [14–16]. In this 3D printing process, molten glass is loaded into a hopper on the top of the device after being gathered from a conventional glassblowing kiln. In operation, both the hopper and the nozzle, through which the glass is extruded, have to be maintained at very high temperatures. The energy involved to maintain the glass in the molten state before and during the extruded process remains high when compared with conventional procedures to mold glass. Furthermore, this equipment is not able to build objects with smooth surfaces [15, 16]. Another recent development of new AM equipment to print glass came from Israel with the Micron3DP. This printer is also based on the FDM technology, but despite reaching temperatures around 1600 °C, only the manufacturing of small scales parts are allowed [18]. As with the GD3P, the Micron3DP equipment is not able to manufacture smooth surfaces. In both types of equipment the glass filament temperature and the geometry are crucial parameters to ensure sufficient adhesion between the new layer and the part already printed. This is a real challenge together with other processing parameters such as the glass viscosity, flow and feed adjustment rates to produce quality parts.

Recently, The Netherlands Organisation for applied scientific research TNO developed a printing process using powders to set color images in glass. This printing process involves a projection of a color, in the form of glass powder, which is applied to a flat glass sheet. Thereafter, the glass sheet is heated in an oven to melt the glass powder with the underlying glass. Using only 3 basic colors, it is possible by their blending to provide any desired color. Furthermore through this fusion process it is also possible to create embossed structures on the glass sheet [19].

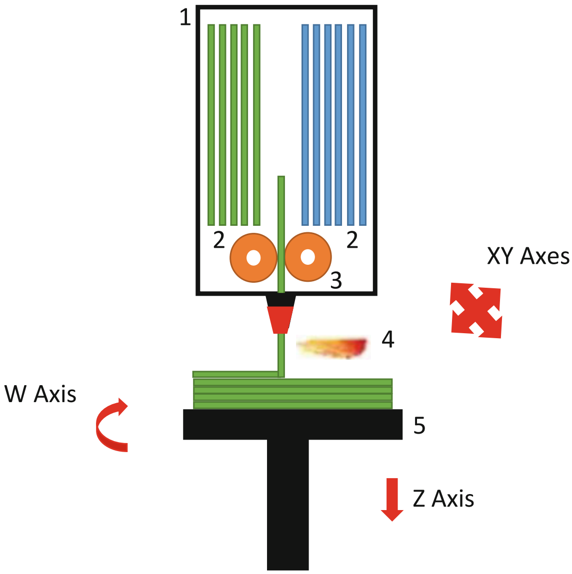
Regarding the use and marketing of additive technologies applied to the production of decorative and utility pieces glass with high detail, high precision and excellent finishing little has yet been done. The development and implementation, in a production line, of efficient equipment for glass additive manufacturing to obtain a mass production of glass parts differentiated with high added value is absolutely crucial for the survival of this Portuguese economic sector. In addition, a drastic reduction in the level of waste raw material during the manufacturing process is expected as well as a significant saving of energy and production time since each product line can continuously manufacture various geometries. With these objectives the equipment, which is described in the next section, was designed and developed.

4 Equipment Conceptualization and Design

The AM equipment developed in this work allows the production by extrusion, layer by layer, of glass parts with a countless combination of colors and shapes through an automatic procedure using glass in the form of rods, as shown in Fig. 2. The equipment designed includes a trajectories generator composed of a set of four or more axes (xyzw or more), which is monitored and controlled by a processing and control software that, in turn, includes a connection interface to the operator and another interface that establishes the communication of the device with other computer exterior systems. The equipment operator can set and control the most appropriate operating conditions to each specific production.

As shown in Fig. 2, the glass in the form of rods of different colors and diameters (2) are stored in the reservoir (1). The rods are driven by an automated material feeder (3) to the extruder nozzle, where a heat source (4) provides the glass molten state, which will be extruded onto the construction platform (5). The equipment also comprises an automatic change system of building platform

Fig. 2 Illustration of color 3D glass printer with 4 axles



(palletizing) with motion in the axis direction or another (Z or other), i.e., in a vertical or other direction.

The construction platform (5), after complete part production, is replaced by another platform leading to the start of a new production cycle. The platform that contains the finished glass part is placed in a transport system, a conveyor belt, to be brought to an oven where it will be subject to a programmed heat treatment. Note that the construction platform (5) is heated to a temperature suitable for production, which contributes to the total energy costs associated with the production process. If the glass rods (2) are colorless it is possible through a glass powder projection system (6), aided by an additional heat source (7), to incorporate a multitude of colors to the processed glass as shown in Fig. 3. This equipment has been submitted to a provisional patent whose reference is 20161000017437.

A rudimentary prototype of the equipment described above was constructed. The idea of building this prototype was to test the feasibility of the operation principle and mainly the effectiveness of the heat source used to melt the glass. Figure 4 illustrates images of the prototype system printing a 3D glass part from a rod glass that is molten using a combustion torch powered through a mixture of oxygen and propane, A significant energy loss was observed with this kind of heat source. To overcome this drawback a new system to melt the glass was designed. Figure 5 displays the scheme of the new system that will be built. The efficiency of induction resistances or high temperature resistances for the heat source will be evaluated.

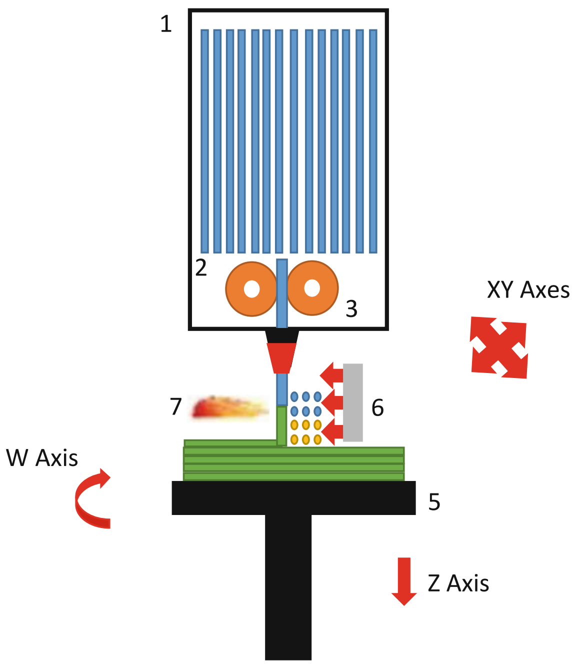


Fig. 3 Illustration of 3D glass printer with the glass powder projection system

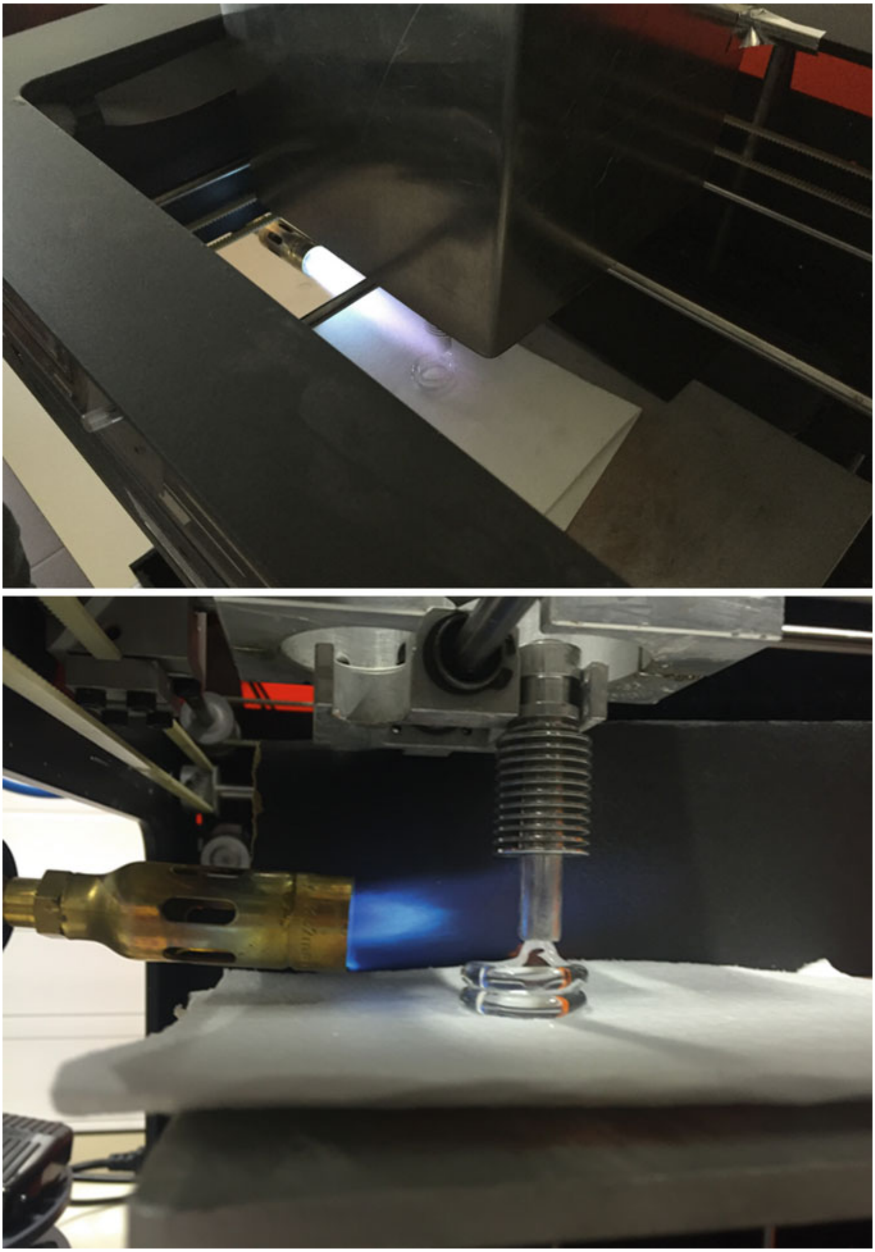
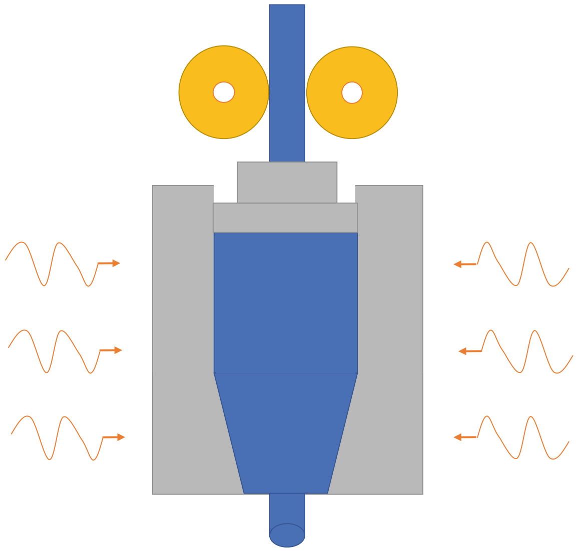


Fig. 4 Images of the rudimentary prototype developed printing a 3D glass part

Fig. 5 Design of the new system to melt the glass



From Fig. 4 it was concluded that as reported for the Micron3DP and GD3P devices, for the equipment developed there is sufficient adhesion between layers and the part already printed. Uneven surfaces are also observed. Nevertheless, the thickness of each layer can be reduced to a dimension comparable to the glass rod diameter. An auxiliary system, using hot air pressured has been proposed to increase the surface smoothness. The energy consumption involved to melt the glass is clearly reduced.

Since the viscosity of the glass changes very quickly with temperature, a very accurate procedure to control the temperature of the glass is required. In addition, the success of the manufacturing process of the desired customized glass part depends on the optimisation of other processing parameters such as the flow and feed rates, which are de as a function of the complexity and dimensions of the part.

Much work is still required to develop and understanding of the influence of the extrusion parameters on the parts produced as well as the physical, chemical and mechanical characterization of the glass parts printed with this equipment. Despite this, an important contribution to the development of 3D printing glass parts has been made. With the additive manufacturing equipment described here it is possible to produce custom parts and with greater freedom of geometries in a short time and at perfectly acceptable costs due to the drastic reduction of hand labor and energy consumption that are associated with the glass industry. This is a highly competitive advantage over current conventional and traditional processes used not only in utilitarian glass pieces but also, and above all, in the production of decorative pieces, thereby opening up new creative horizons for designers.

5 Conclusions

This work presents the development of novel AM equipment that combines the current technology of additive manufacturing and the art of working glass by hand. From the equipment implementation viewpoint, a lower production complexity, greater constructive reliability and high adaptability to the different design solutions can be expected. Additionally, the manufacturing process of stylized glass parts is automated, which leads to productivity increase and a considerable reduction on the intervention of manpower and on the energy consumption. This equipment will be able to produce translucent and multicolored three-dimensional art pieces. The equipment will, in an automated fashion and from glass in the form of rods, provide the production of glass components that can have numerous combinations of colors and shapes, since the machine operator can set and control the most appropriate operating conditions to each specific production. For the manufacture of multicolor glass parts, the equipment can, additionally, include one or more heat sources that allow the fusion of the glass powders projection of the different colors on successive layers deposited.

In short, the equipment described here will open a range of possibilities of studies on the application of additive manufacturing to the glass area to produce decorative and utilitarian objects in materials with high melting points without the need to resort to traditional ovens, and thus, contribute to a drastic reduction in energy bills. With the implementation of glass additive manufacturing equipment and due to the absence of drastic reduction of waste and of raw materials, a significant saving of energy and production time is expected. With the implementation of automation in the production process, a certain number of production lines that lead to the mass production of different glass parts with high added value becomes possible, and this undoubtedly contributes to the growth and development of this economic sector.

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