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DESIGN DEVELOPMENT OF A CERAMIC DLP 3D PRINTER INTEGRATING QFD AND TRIZ

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Abstract. *Additive manufacturing (AM) of ceramics allows the fabrication of complex ceramic parts on a small series without the high costs of molds. However, most commercial 3D printers capable of manufacturing ceramics are costly. Among the AM processes, Digital Light Processing (DLP) stands out for its ability to produce complex high-performance ceramic parts. In this work, a ceramic DLP 3D printer was designed integrating quality function deployment (QFD) and theory of inventive problem solving (TRIZ) methods. The user's requirements were obtained from questionnaires applied to stakeholders of small industries and research laboratories and translated to technical design requirements. Next, their interrelation was analyzed, indicating technical contradictions from the demand for low-cost equipment with adequate precision and productivity. Applying TRIZ, each contradiction was converted into a pair of engineering parameters and then the contradiction matrix indicated possible principles of invention, of which "another dimension", "dynamics", and "preliminary action" emerged. Thus, a DLP 3D printer with an innovative recoating system was proposed in which two blades with sequential and distinct functions, with automatic active blade change, would create constant and homogeneous layers. A prototype was built and tested with highly loaded photosensitive ceramic suspensions (solid loading of 40 vol% and viscosity over 2 Pa.s), producing ceramic green parts with complex features and high relative density after the post-processing (over 95%). Thus, the proposed design proved capable of producing advanced ceramics parts, being an economical and viable alternative for use in laboratories and small businesses.*

Keywords: *additive manufacturing, ceramics, design, QFD, TRIZ.*

1. INTRODUCTION

Ceramic materials are known for their high-temperature resistance and for usually having electrical and thermal insulation (JR. CALLISTER; RETHWISCH, 2013). Advanced ceramics are special ceramics that exhibit superior properties and are often produced in small quantities at higher prices, having applications in several areas as solid-oxide fuel cells, automotive sensors, prostheses, dental applications, etc. (CARTER; NORTON, 2013). There is a growing demand for ceramic parts with complex geometries in small series. In this context, additive manufacturing stands out for being able to produce ceramic parts without the high costs of molds (SCHWENTENWEIN; HOMA, 2015; ZHANG et al., 2020).

Digital Light Processing (DLP) is a photopolymerization additive manufacturing process in which the layers are formed by selectively curing a photosensitive material by projecting images (GIBSON; ROSEN; STUCKER, 2015; ISO, 2015). This process should be highlighted for its ability to print complex ceramic parts with excellent dimensional precision and good surface quality (LIAN et al., 2017; SANTOLIQUIDO; COLOMBO; ORTONA, 2019). However, there are several key factors in the success of ceramic manufacturing by photopolymerization such as the formulation and slurry preparation, that should have the suitable rheological behavior, stability and photosensitive parameters (CAMARGO et al., 2021a; KOMISSARENKO et al., 2018; WEI et al., 2019), the post-processing (debinding and sintering) (AZARMI; AMIRI, 2019; CAMARGO et al., 2021b; JOHANSSON et al., 2017; KOMISSARENKO et al., 2018), in addition to the additive manufacturing with the proper equipment and parameters.

DLP can be divided by building direction. In the bottom-up approach, falls from below through the transparent bottom of the vat (SANTOLIQUIDO; COLOMBO; ORTONA, 2019). Therefore, there is a detachment between the formed part and the bottom of the vat at each layer, which introduces stresses and deformation to the parts, mainly when working with high viscosity raw materials as ceramic raw materials (photosensitive suspensions with a high content of solid load)

(DUMENE; EARLE; WILLIAMS, 2018; SANTOLIQUIDO; COLOMBO; ORTONA, 2019). On the other hand, in the top-down approach, the light falls on the top (SANTOLIQUIDO; COLOMBO; ORTONA, 2019). In this case, the big challenge is creating constant and homogeneous micrometric layers and a recoating system is required (CAMARGO et al., 2021c).

Most commercial DLP devices are bottom-up equipment and thus not capable of successfully producing advanced ceramics. The few exceptions are costly industrial equipment (DIPTANSHU; MIAO; MA, 2019) with complex recoating systems (CAMARGO et al., 2021c) whose sale value exceeds $100.000,00 as CeraFab 7500 (Lithoz) (BORLAF et al., 2019, 2020; JOHANSSON et al., 2017; SCHEITHAUER et al., 2018; SCHWARZER et al., 2017; SCHWENTENWEIN; HOMA, 2015), Ceramaker system (3D CERAM, France) (AZARMI; AMIRI, 2019; LIU et al., 2020; XING et al., 2017, 2018, 2020), and ADMAFLEX 130 (ADMATEC) (LI et al., 2019, 2020a, 2020b). In this work, questionnaires were applied to possible ceramic 3D printing users to understand their demands, and subsequently, a ceramic DLP top-down 3D printer was designed based on a systematic approach integrating quality function deployment (QFD) and theory of inventive problem solving (TRIZ) methods.

2. MATERIALS AND METHODS

In this work, the ceramic DLP 3D printer design development was based on design methodology structure proposed by Ulrich and Eppinger (2015) and Pahl et al. (2007), on early activities design: i) Planning and task clarification, related to the problem definition (demand and opportunities) and ii) Conceptual design phase, the fundamental phase to provide technical improvements or innovation solutions to the problem. The following phases (“embodiment design” and “detail design”) are increasingly related to preliminary and detailed design and are beyond the scope of this work.

2.1 Task Clarification

Quality Function Deployment (QFD), specifically the House of Quality (HoQ) was the systematic method adopted in this design phase. The HoQ is the first matrix of a set of four, each from a different field of engineering. The method was chosen due to the structured approach to include the end-user in the initial design process. End-user and technical domains compose this matrix where operations (extraction, correlation, etc.) are developed to generate technical characteristics. The matrix elaboration starts with an interactive process with can be used by different approaches and methods, e.g. observations, questionnaires, virtual and physical meetings (CHENG; MELO FILHO, 2010). This process generates a user´s requirement list, where each one has attributed a grade. Don Clausing (1994) proposed a grade criteria: 9, 3, or 1 for “very important”, “important” and “little important”, respectively. In this work, the user’s requirements and their relative importance were obtained from questionnaires applied to stakeholders of small industries (engineers and managers) and research laboratories (professors, graduates, and undergraduate students) related to the manufacture of advanced ceramics.

Next, the user´s requirements were translated to a set of technical characteristics composing the central matrix of the HoQ. In this way, each user requirement was correlated with the set of technical characteristics by following scores: 9, 3, 1, or 0 for “strong”, “moderate”, “weak”, and “no relationship”, as suggested by Mesbahi et al. (2020). This way, the importance (relative weight) of each technical design requirement was calculated, taking into account the sum of the products between the user’s requirement importance score and relationship score with the considered design requirement. The matrix, therefore, provides prioritization of the importance of technical characteristics extracted from the set of user requirements.

The superior matrix of HoQ (also known as “correlation matrix” or “roof of the HoQ”) allows the comparison of technical characteristics pairs identifying technical contradictions in advance. These contradictions (when improving one technical requirement tends to worsen the other) were pointed out. Applying TRIZ, the contradictions involving technical characteristics with a high relative weight were converted into a pair of engineering parameters that had some possible principles of inventions indicated by Altshuller’s Table of Contradiction (AL′TSHULLER, 1999; G. NAVAS, 2013). Such principles were subsequently taken into consideration in the search for possible solutions which take place in the next design phase.

2.2 Conceptual design

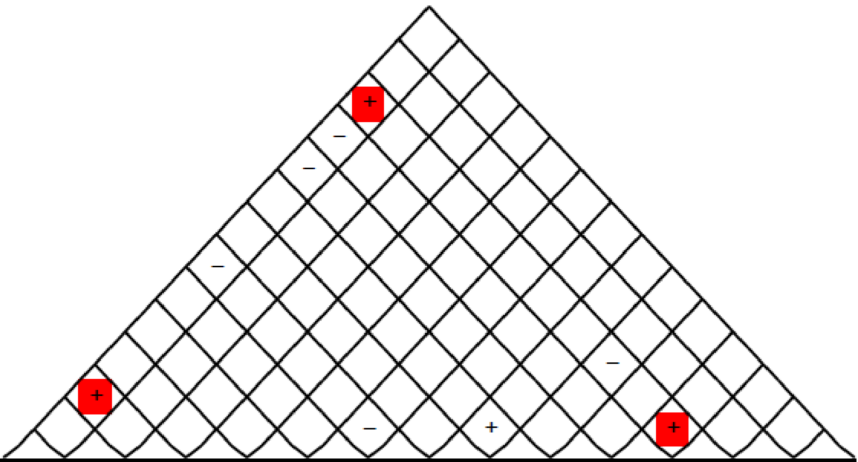
To clearly identify inputs, outputs and their relationship of the product to be designed, functional analysis was performed, indicating the overall function of the printer which was divided into subfunctions, having their flows of energy, materials and signals identified, as suggested by some well-known design references (PAHL et al., 2007; ULRICH; EPPINGER, 2015). Subsequently, a Morphological Matrix was used to generate systematic combination (PAHL et al., 2007) of the principle solutions. Lastly, the solution variants were evaluated resulting in the specification of the principle solution.

3. RESULTS AND DISCUSSION

The integration of the design tools created a foundation for the successful design of a ceramic DLP 3D printer, as described in this section:

3.1 Task Clarification

The user's requirements, the technical design requirements, their scores, and their relationships are presented in the HoQ of QFD (Figure 1). The contradictions from the demand for low-cost equipment with adequate precision, productivity, and able to work with multiple materials are highlighted in red in the roof of the QFD and the application of TRIZ on them is presented in Table 1, indicating possible invention principles, which in the next step, generated principle solutions.



User's Requirements \ technical design requirements	Price (US$)	minimum volume of raw material (ml)	Number of raw materials	Equipment volume (m³)	Time needed for cleaning (min)	Time needed for maintenance (min)	Number of off-the-shelf parts	N0. of tasks required to operate	Time required by the operator (min)	XY Resolution (µm)	Z resolution (µm)	Printing Speed (mm/min)	UV intensity to the environment (W)	Exposure Dose (mg)	Relative Importance
Direction of improvement	▼	▼	▲	▼	▼	▼	▲	▼	▼	▼	▼	▲	▼	▼	
Low cost	9						3			3	3				3
Able to work with little raw material		9		3											9
Able to work with different materials			9												9
Compact		3		9											1
Easy to clean					9									3	3
Easy to do the maintenance				3		9	9								3
Easy to use					3			9	3						3
Operator independence								3	9						3
High Precision	3									9	9				9
Productive	3				1	1						9			3
Safe	1												9	9	9
Relative Weight	8.6%	10.0%	9.7%	5.4%	4.7%	3.6%	4.3%	4.3%	4.3%	10.8%	10.8%	3.2%	9.7%	10.8%	

Figure 1. HoQ of QDF.

Table 1. Application of TRIZ on contradictions from QFD roof

Contradiction	Conflicting Design Requirements	Engineering Parameters	Invention Principles
1	Price	Complexity	Dynamicity, Mechanical System, Pneumatic or hydraulic, Thermal expansion
	Number of raw materials	Adaptability	
2	Price	Complexity	Equipotentiality, Another dimension, Mechanical system
	Printing speed	Productivity	
3	Z Resolution	Accuracy of manufacturing	Preliminary Action, Mechanical Vibration, Color Changing, Inert atmosphere
	Printing Speed	Productivity	

3.2 Conceptual design

The overall function of the printer was defined as "transform photopolymerizable ceramic suspension to parts based on 3D models" and the functional diagram with subfunctions is shown in Figure 2. Such a tool assisted in the selection of the project parameter considered in the systematic combination. The Morphological matrix is presented in Figure 3 with the chosen selection highlighted. Some of the invention principles pointed out in the TRIZ were used in the design of the recoating system. Such process is strongly linked to the contradictions found, since it may have a high influence on the cost of the device (price), and it is essential in the formation of micrometric layers (Z resolution) in a viable time (printing speed), even for different materials as viscous photosensitive suspensions (able to work with multiple materials).

A low-cost solution based on a two-blade systems (instead of one, as usual) allows the use of the device for different materials with even those with high viscosity. The blades have sequential and distinct functions: the first blade spreads and the second blade levels and calibrates the thickness. The position change that defines the active blade was based on some of the principle solutions indicated from TRIZ. Thus, the movement of blades for positioning occurs because of the intrinsic movement for layer formation, without wasting time for this specific action ("preliminary action"). For this, the blades and the holder can have relative movement to each other ("dynamicity") and the blades can rotate in an additional dimension ("another dimension"). The concept is presented in Figure 4.

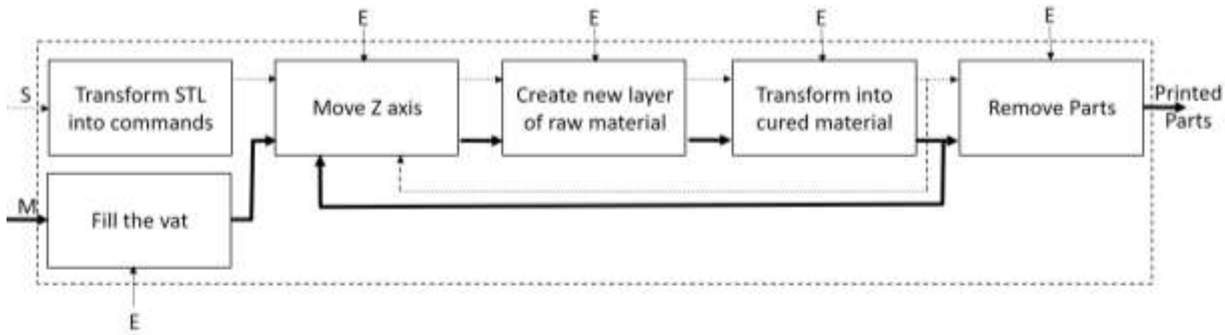


Figure 2. Functional diagram with subfunction (M, E, and S represent material, energy, and signal, respectively).

Parameter	Solution			
Transform STL into commands	Software NanoDLP	**Software Creation Workshop**		
Construction direction	Bottom-up	**Top-Down**		
Z axis: Actuator	**Stepper Motor**	Servo Motor		
Z axis: Linear Motion	Screw, nut and linear guides	**Linear Motion Guide Actuator**	Rack and Pinion	
Recoating System Type	**Blade**	Roller	Pump/Vacuum Dispenser	
Recoating System Actuator	Pneumatic	**Stepper Motor**	DC Motor	
Recoating System: Linar motion	Cam	Screw, nut and linear guides	**Timing pulley, belt and linear guides**	Slider Crank

Figure 3. Morphological Matrix.

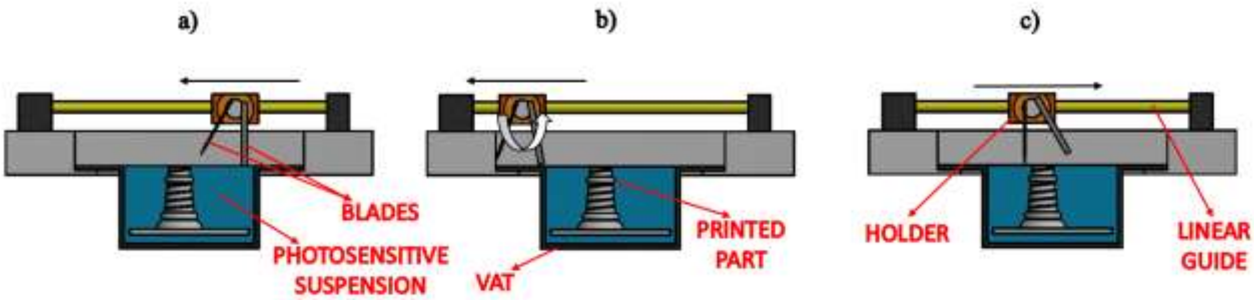


Figure 4. Schematic diagram of the recoating system concept.

3.3 Functional prototyping of a Ceramic DLP 3D printer

The built of the prototype based on the design proposed in this work and its validation were recently published (CAMARGO et al., 2021c, 2021d). The prototype (Figure 5) worked properly with highly loaded photosensitive ceramic suspensions (solid loading of 40 vol% and viscosity over 2 Pa.s). The recoating system successfully creates homogeneous layers of 100 µm and the device produced ceramic green parts with complex features (Figure 6) and high relative density after the post-processing (over 95%). Thus, a DLP apparatus under US$5,000.00 capable of producing advanced ceramics was created and may be used as a viable alternative for laboratories and small businesses.

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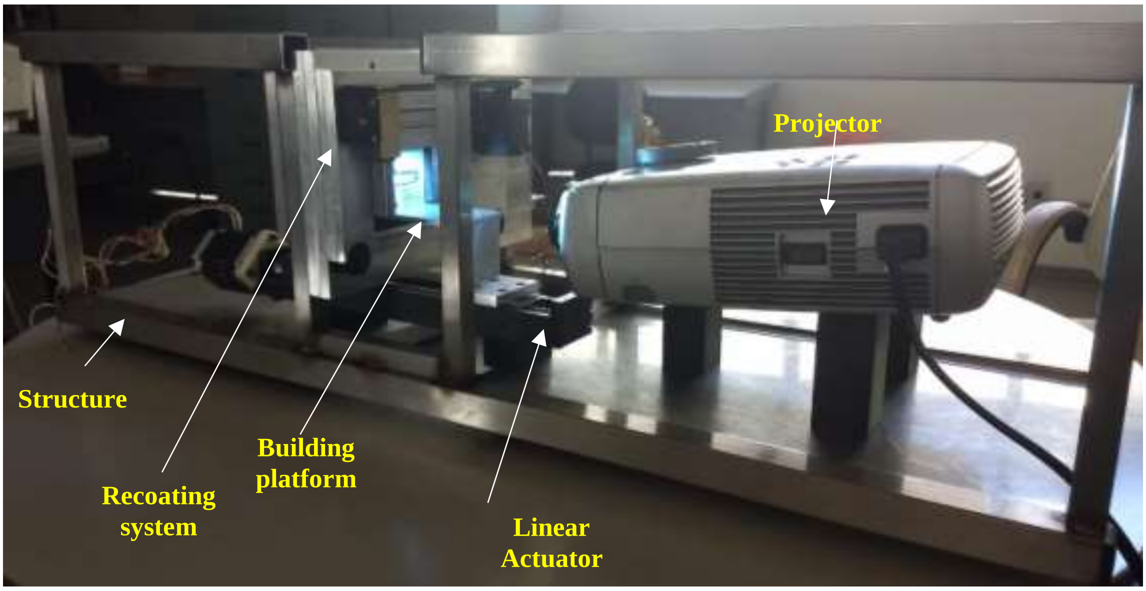

Figure 5. Prototype under assembly.

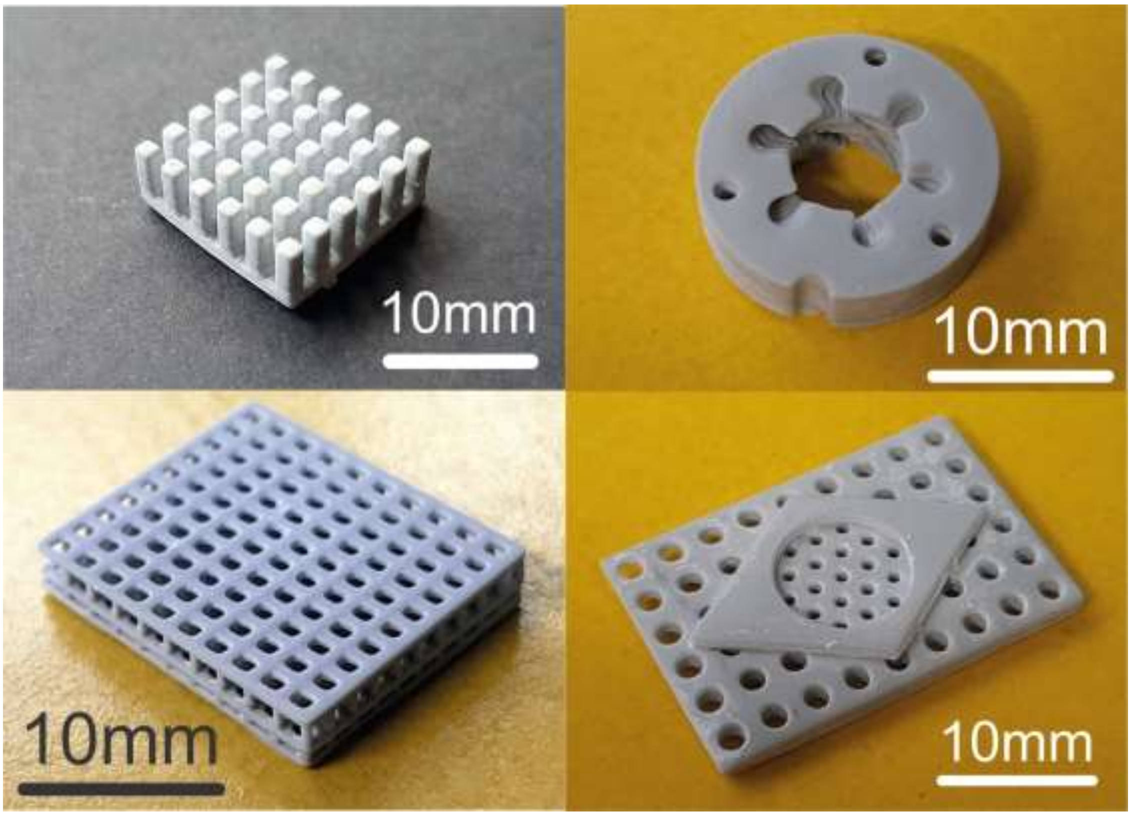

Figure 6. Green printed parts.

4. CONCLUSIONS

In this work, a systematic approach was used to design a ceramic DLP 3D Printer. For this, the user's requirements were obtained from questionnaires, QFD was used to relate them with technical design requirements and identify their contradictions. Applying TRIZ, these contradictions suggested possible principles of invention, some of which were used to create the concept of a DLP 3D printer with an innovative and low-cost recoating system able to would create constant and homogeneous layers in a viable time even for viscous photosensitive suspensions. Thus, the proposed design proved capable of producing advanced ceramics parts, being an economical and viable alternative for use in laboratories and small businesses.

5. ACKNOWLEDGEMENTS

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