

Redesign of an innovative new extrusion system for a printing machine for ceramics

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Abstract

Today, the introduction of ceramic materials in the medical field is becoming a vital necessity because of its stable physicochemical characteristics, high biocompatibility, and good osteoconductivity. On the other hand, machining of ceramic components is difficult, owing to their extreme hardness and brittleness. Additive Manufacturing (AM) technologies are an appropriate alternative to obtain the complex shapes of implants, which can have porous structures. Thus, since the development of 3D printing, Direct Ink Writing (DIW) is one of the most promising and inexpensive techniques for shaping free-form ceramic medical components such as prostheses or dental implants from liquids or pastes. However, the assurance of performance criteria of the extrusion system for simultaneous usage becomes the major challenge for most Direct Ink Writing (DIW) platforms, for instance for printing large parts, for multi-material printing, to decrease printing time, and to increase efficiency in terms of motor usage and weight of the extruders. To address the current deficiencies, a new extrusion system is redesigned for a 3D printing machine for ceramics that is compatible with different low-cost, open-source 3D printers. The proposed extrusion model enables printing with a loader with different syringes simultaneously, without stopping the operational process while switching the syringe. Pugh concept analysis was used to select the optimum design shape. After that, the 3D CAD environment was used to combine the strength of Pugh's method and the design space. This brings a new concept into the mechanical design field for 3D printers, which is in line with the technological trends prevalent in industry.

Introduction

Additive manufacturing (AM) or 3D printing has rapidly gained attention across the science and engineering communities, since it is a unique manufacturing technique that enables the flexible preparation of highly complex structures that are difficult to obtain using traditional fabrication methods such as casting or machining [1]. The NF ISO / ASTM 52900 standard [2] defines additive manufacturing (AM) as the "process of joining materials to make parts of 3D model data, usually layer upon layer, as opposed to subtractive and formative manufacturing methodologies". The use of 3D printing to manufacture ceramics receives increasing industrial and research interest, because, compared with metals and polymers, ceramics have a broad range of favorable properties, including high melting temperature, high mechanical strength, good chemical properties, and high thermal stability [1, 3, 4]. On the other hand, machining of ceramic components is difficult, owing to their extreme hardness and brittleness [1, 4]. Technical ceramics, and especially zirconium-dioxide (ZrO_2 , zirconia) find different applications in the medical field [5, 6], due to its stable physicochemical characteristics, with the low release of debris, high biocompatibility [7], and good osteoconductivity [6]. Zirconia is nowadays used as material for e.g. prostheses [8, 9, 10], organ printing [11, 12], dental crowns [13, 14], sensors [15, 16], and several micro components [17, 18].

The different AM processes, such as inkjet-based inkjet printing (IJP) [19], three-dimensional printing (3DP) [20], selective laser sintering (SLS) [21, 22], selective laser melting (SLM) [23, 24], stereolithography (SLA) [25], lithography-based ceramic manufacturing (LCM) [26], laminated object manufacturing (LOM)

[1], free-form extrusion (FFE) [27] and fused deposition of ceramics (FDC) [28] have been recently used for the production of ceramic components. Among these printing methods, direct ink writing (DIW) or robocasting is one of the most popular approaches for freeform fabrication of ceramic components due to the simplicity, low cost of their fabrication system, high density of the fabricated parts, and its capability to produce parts with multiple materials [29, 30]. It is an AM technique in which ceramic powder mixed with a polymer is extruded through a nozzle. The ink is usually supplied through a syringe or container and does not need to be heated to a high temperature to be extruded through the nozzle for printing. Therefore, cells and bacteria can survive during the printing process, making DIW suitable and widely adopted for biology and biomedical applications [31]. According to the literature review [4, 30, 32, 33], 3D printing extrusion machines for ceramic paste or ink can be categorized into three constructive designs, namely plunger-based, screw-based and pump-based extrusions machines. Regarding the plunger extrusion, several open-source designs have become available online for retrofitting consumer 3D ceramic printers. In the present work, DIW is applied to the manufacture of prostheses using ceramic material. Several DIW printers designed for medical research are available in the market such as BioBot 1 [34], EnvisionTEC 3D-Bioplotter [35], and Vormvrij LUTUM [36]. They are professional ceramic 3D printers which have different components to adapt to several types of clay having different viscosity values. A double extruder is available as an option. However, they are usually expensive [31]. On the low-cost printer side, the Zmorph VX multi-function 3D printer [37] has many features, thanks to its interchangeable tool heads. Aside from conventional 3D printing, laser engraving, laser cutting, the ZMorph VX can print clay with its dough extruder. Tytan 3DGaia Multitool [38] **is a delta 3D printer made by Tytan 3D**. In addition to ceramic, the Tytan 3D Gaia Multitool is capable of 3D printing several different materials (including chocolate). The DeltaWasp 20 40 [39] is a delta desktop 3D printer produced by WASP. Basically, it is not a multi functional machine, but WASP develops an additional module, WASP Clay Kit 2.0, which is compatible with the DeltaWasp 20 40 for 3D printing of clay, ceramic mixtures, porcelain, gres, earthenware, and other materials. Finally, regarding DIY (Do It Yourself) 3D printers, some examples are the Fab@Home [40] was introduced as a multi-material open source printer led by students at Cornell University [31], the RepRap, also developed by students [41], and the “Universal Paste Extruder” [42] by RichRap. The latter has a sort of syringe pushed by a drive belt mechanism to move the plunger that presses the feedstock through a nozzle. It simply uses the existing extruder motor output from printer electronics, and it can print ceramic clays.

The main contribution of this work is the redesign of the extruding system to modify a low-cost Dual Paste Extruder BCN3D printer [43], which comprises the syringe and the mechanism that provides the necessary pressure to extrude the paste. It is a modular printer developed by CIM-UPC, an entity that is associated with the Universitat Politècnica de Catalunya (UPC)-BarcelonaTech. One of the main disadvantages of the original design was the limited volume of the syringe vessel barrel. For quality reasons, it is impossible to print larger products, because it is not desirable to stop printing in order to fill it again. The present design project aims to promote the applications of the printer and to extend it to medical engineering research. To achieve the development of the new extrusion head for ceramic with higher capacity, a rigorous customized product development process was performed in a previous work

[44], based on design tools, techniques and methods available in the literature [45, 46, 47, 48]. To arrive at this novel concept, six extruder concepts derived from the extruder system for BCN 3D that will lead to an innovative extrusion head were generated by means of a Morphological Matrix [49].

The first aim of this work is to evaluate and improve different concepts and to choose the best one among them. It was identified by the Pugh matrix [50], which is a type of prioritization matrix that was first proposed by Pugh in 1981 [51]. It is associated with quality function deployment (QFD) [52, 53]. Pugh matrix has been used, for example, in medical device development [54], to evaluate the design selection of a hydrostatic bearing pad for automotive application [55] or to design a novel solar thermal collector [56]. Kim et al [51] propose an error-outlier-based algorithm with Pugh's concept selection that can choose the impact localization point on a composite plate with the low error among several candidate impact points. Thakker et al used Pugh's method to achieve the economic and viability of power generation from wave energy by designing and developing new and improved machinery [57].

The second goal of the present work was to construct a visual prototype of the extrusion head to communicate both abstract and concrete ideas and to establish monetary values for comparison to the standard design, especially in the early stages of the design process.

The paper is organized as follows: section 2 presents the Pugh's method of concept selection to evaluate the benefits and drawbacks of the proposed designs and to choose the best one, with reference to the original customer and technical requirements; subsequently, the most preferred concept is finalized and analyzed with the use of the 3D-CAD environment; the paper concludes in section 4 by discussing the developed methodology and implications and benefits of the new head extruder of the printer.

Evaluation And Rating Of The Design Concepts

1.1 Initial state

The printer used in this project is a Dual Paste Extruder printer (Fig. 1a). It is a modular printer developed by CIM-UPC, an entity that is associated with the Universitat Politècnica de Catalunya (UPC)-BarcelonaTech. Its extruder mechanism consists of a rack-and-pinion system that directly pushes the syringe plunger and transmits the necessary force to operate it. It is driven by a motor and gears (Fig. 1b) set to reduce the speed of rotation and multiply the torque. This injection system controls the amount of material deposited through the pressure exerted.

However, this extrusion system is very limited when printing voluminous parts as ceramic prostheses (it only allows printing low volumes under 5 cm³ of ink) because it is impossible to print large parts without stopping manually the printing process and refill the syringe, which was negatively reflected on the quality of the final product and took a long time (the time needed to change the syringe is very long).

The objective of the previous paper [58] was to develop the first steps of the redesign of a new type of ceramic-paste extruder system able to print bulky ceramic prostheses such as the acetabulum one. It is

based on a plunger extrusion mechanism of a paste extruder and can easily be adapted to other low-cost 3D machines, which extends the access of this technology to a larger number of designers. Then, the design challenge was to satisfy this main function while combining the maximum performance criteria, such as:

- To be able to print hip prostheses and other ceramic parts;
- The possibility to be installed in the extrusion system on the BCN3D machine;
- To be easily adaptable to other types of machines;
- To allow flow stability;
- To facilitate setting and holding of the syringe;
- To allow stability of the syringe;
- To optimize the forces applied to the machine;
- To allow nonstop printing;
- To print with different materials;

1.2 Evaluation of different concepts

After generating different concepts in our previous paper [58], the next step is to evaluate them. The evaluation consists of comparing the different alternative concepts with each other, based on the target specifications to which they must respond. To do this, the decision matrix method or Pugh's method [59, 60, 61] is applied. It is often called Pugh concept selection and has proven to be effective for comparing alternative concepts. It evaluates and improves the different concepts, and helps to choose among all the global concepts found, from which one will be given priority. In essence, the design development process using Pugh's method results in better outcomes rather than other weighted decision-making [62, 63]. It makes it possible to identify the relative strengths and weaknesses points of the different concepts. Comparison of the scores in this manner gives insight to the best alternatives, allows the generation of new concepts resulting from the combination of the best aspects identified, and provides useful information for making decisions. The iterative process steps are shown in Fig. 2.

Step 1: To Select the Alternatives to Be Compared. The alternatives to be compared are the different ideas developed during concept generation in our previous work [58], by means of a Morphological Matrix [64]. It is important that all the concepts to be compared be at the same level of abstraction and in the same language. It means it is best to represent all the concepts in the same way [63].

Four concepts of the extruder head for the ceramic 3D printer were consequently developed taking into account the customer and technical requirements and their weightings. Each extruder concept comprised a syringe. Schematics of the four concepts and a BCN 3D printer design used as a baseline are shown in Table 1.

Step 2: To Choose the Criteria for Comparison. First, it is necessary to know the selection criteria on which the alternatives are to be compared with each other. However, because each criterion is given equal

weight in the concept screening method, care should be taken not to list too many relatively unimportant criteria in the screening matrix. Otherwise, the differences among the concepts relative to the most important criteria will not be reflected in the outcome [47]. An effort was made to develop a full set of customer requirements for the design of the head extruder for ceramics by Quality Function Deployment (QFD). These selected criteria for evaluation were based on functional requirements and/or objectives of the customer needs. Table 2 shows the most important specifications.

Step 3: To Prepare the Selection Matrix. First, the Pugh matrix was prepared. The concepts generated by the morphological matrix method are entered along the top of the matrix, using graphical and textual labels of some kind. The selected important criteria drawn from the QFD method are listed along the left-hand side of the screening matrix, as shown in table 3.

Step 4: To Evaluate Alternatives. By this time in the design process, a concept to become the benchmark is chosen, DATUM or reference concept, against which all other concepts are rated. All other designs being compared with it as measured by each of the customer requirements [65]. The use of a datum (original or experimental reference concept) is due to the difficulty to consistently compare concepts to one another [66]. The reference is generally either an industry standard or a straight forward concept with which the team members are very familiar [47]. However, since the problem is about redesign of an existing product, then the existing product, abstracted to the same level as the concepts, can be used as the datum.

A Pugh matrix is completed by scoring the technical requirements as better, about the same, or worse, in each concept, in comparison to the reference design (DATUM) [56]. If it is better than the datum, the concept is given a “+” score. If it is judged to be about the same as the datum, an “S” (same) is used. If the concept does not meet the criterion as well as the datum does, it is given a “–” score [63]. Table 3 shows the first iteration in the process decision matrix.

Step 5: Rank the Concepts. After rating all the concepts, the number of “better than,” “same as,” and “worse than” scores are summed. After that, the sum for each concept is entered in the lower rows of the matrix [47]. For example, from table 3 the concept C1 was rated to have three “better than” criteria, three “the same as” criteria, and one “worse than the reference” concept.

Next, a net score can be calculated by subtracting the number of “worse than” ratings from the “better than” ratings. Once the summation is completed, the concepts are ranked according to the net score.

At the end of this first phase, weak concepts such as C4 were eliminated from the matrix. Among the alternatives, the “concepts C1, C2, and C3” received the highest weighted ranking (see Table 3). Then, they were improved, therefore creating new concepts.

Comparing concepts C1, C2, and C3, the concepts C1 and C3 were chosen as the best ones because they are an innovative solution, unlike concept C2. Even a winning concept C3 can score poorly in one criterion. What can be done to improve those aspects?

- For the criteria “counter space” the size of the extrusion system (concept C1 and C3) must necessarily be respected to install it on the BCN3D printer machine. So the idea is to install the loader containing the syringes outside the machine so as not to change the dimensions of the machine.
- Another improvement to add to the C3 concept is to use a charger with variant syringes (5 ml, 20 ml ...) as needed, i.e. if small parts are to be printed, the 5 ml syringes will be used. For large parts, the 20 ml syringes will be used (the dimensions of the syringes can be adapted according to needs).

In this case, changes to the concept C3 constituted the creation of a new concept, which was added as a new column in the matrix and evaluated. Nevertheless, the idea was to eliminate more concepts on each iteration than were added to eventually converge on a “best” design [57]. The list of design concepts that passed the first iteration was revised and then we established a new datum (the highest rated concept). Table 4 shows the second iteration in the process decision matrix.

According to the matrix (Table 4), concept 6 is the newly designed extruder head for the BCN3D printer. The design is a loader with syringes of different dimensions that allow continuous printing of small or large parts according to the needs of customers. This matrix differs from the weighted decision-matrix [20], where the criteria are given weight. Furthermore, a major advantage of this controlled convergence method over matrix selection methods is that it allows alternating convergent (analytic) and divergent (synthetic) procedures. As the reasoning proceeds and a reduction in the number of concepts comes about for rational reasons, new concepts are generated.

After rerunning the matrix, the improved experimental concept shall be taken to the final stage where in order to work on the best solution chosen. It is possible then to present the 3D design of the extruder (virtual prototyping), as it is considered to be one of the effective ways to communicate both abstract and concrete ideas, especially in the early stages of the design process [57]. For that, computer-aided design (CAD) and analysis tools are used, to simulate the system and see how it interacts with its environment. They are useful for digital prototyping and engineering analysis because they allow virtually creating and interactively analyzing the extruder in its operating environment, without first need for physical prototypes. This is to avoid the expenses involved in producing physical prototypes [57, 67].

Design Of The New Extruder Head For Ceramic With Variable Syringes

At this level of the design process, the concretization and realization of the concept begins, by presenting information through the concept diagram. These diagrams are then transformed into product drawings. This phase consists of identifying all the spatial data (making an overall drawing).

2.1 The basic structure of the extruder

The approach used here for printing large ceramic pieces is characterized by the use of an extruder of the syringe loader. This printing extruder will be installed in a BCN 3D printing machine and will be compatible with different low-cost, open-source 3D printers.

The new head should be able to print large pieces with ceramic and different materials without stopping the impression in order to decrease the printing time. Furthermore, the extruder should be as light as possible, considering the speed and dynamics of 3D printing. In addition, the extruder should be fixed outside the machine because of the minimal reduction of the usable workspace of the printer. By using "G-Codes" to control the rotary movement, it can be used in most FFF systems available in the market. Figure 3 shows the kinematic diagram of this new extruder system. The present diagram relates to an automatic syringe storage extruder system. It adopts three subsystems. The automatic syringe loading system (1), which is operational to manually receive several syringes of the same or different volumes, allows the syringe feeding system to be loaded and unloaded once the syringe is empty. The syringes are automatically transferred to the holding system (2) using an arm. The holding system allows the fixing of the syringe in order to perform printing with ceramic material. It is connected to the power supply system, composed of an engine that will transmit the necessary torque to the toothed wheels and rack (3a) to multiply it using an epicyclical train (3b).

In the next part, the three subsystems are explained to understand the new design of the extruder before starting the 3D design of the system.

2.1.1 The basic structure of the extruder

This subsystem (Fig. 4) makes it possible to:

- Manually store the syringes (with different volume) in the rolling loader (1).
- Automatically load the feeding system (2) with the syringe filled with ceramic material and unload it when the syringe is empty. Loading and unloading are done using an arm (pivot link) (3).

The feeding system must ensure the isostatic maintenance (tightening) of the syringe which contains the ceramic material. The syringe in space has 6 degrees of freedom, including 3 translations and 3 rotations concerning the orthogonal base. For that, to immobilize the syringe in space, the 6 degrees of freedom must be removed.

The most important surface is the cylindrical surface. To eliminate the maximum number of degrees of freedom a pivot connection is associated with it. There remain $(6-4 = 2)$ degrees of freedom which corresponds to the axial translation and the rotation around the axis of the syringe. Since the syringe is very long compared to its section (long bore), the long centering with 4 Vsupports is used (4). To eliminate the remaining translation, a punctual connection is used, which eliminates 1 degree of freedom (physically it is plane support but from a material point of view it is a punctual support) (5). The last degree of freedom is the elimination of the rotation around the axis of the syringe by the tightening (spring system which is punctual support) (6).

2.1.2 The feed and extrusion sub-system

The syringe currently used has a capacity of 5 ml. The objective is to increase the capacity of the syringe to print the large parts. As a hypothesis, the same orifices (same pressure) will be used. If the orifices are changed, the pressure will also change. Since the pressure is constant, in case the surface is increased, it is necessary to increase the force. That is why, if the dimension of the syringe is changed, it will be necessary to modify the extrusion system.

The feed and extrusion module is made up of different components. The current transmission, which manages to transmit the necessary torque, consists of a stepping motor and an epicyclical train (Fig. 5) to reduce the speed of rotation and multiply the torque, which allows its turn to exert a large force on the rack and, therefore, the force required (linear movement) on the syringe, more precisely, to the syringe plunger and transmits the force necessary for its operation. This high force is necessary due to the type of paste (ceramic material) used by this 3D printer and the volume of the syringe chosen. Therefore, the necessary pressure will be exerted on the dough in order to achieve optimum manufacturing results of objects previously used with CAD tools.

Once the holding system is loaded by the syringe filled with ceramic, printing can start. To do this, the spring compression must be greater than the material flow in order to achieve the point support bond before the print starts. In addition, at the end of printing and to unload the syringe and transfer to the loader, the syringe must return to its current state. To do this, there are four ways (fig. 6):

- Transversal disengagement ;
- Pivot disengagement ;
- Longitudinal disengagement ;
- Disengagement with toothed sector pinion;

The fourth system was chosen as a return system for the extraction of the syringe once the syringe is empty because it is innovative, and

2.2 The CAD model of the head extruder for ceramic

Printed parts used in this machine were disproportionally large. That is why it was decided to use direct drive mechanism. But in order to lower the weight of the whole head as much as possible, the feeding mechanism will be fitted with a single stepper motor.

The figure 8 shows the different position to load and unload the syringes. In the first figure (7a), the arm is in neutral position (the loader is equipped with syringes filled with ceramic material). In the second figure (7b), the transfer of the filled syringe to the printing system is carried out using a rolling arm. Once the printing is finished (empty syringe), the exchange of the empty syringe by one filled with material will be made (figure 7c). CAD model of this new concept is shown in Fig. 8.

In the spirit of RepRap community philosophy, most parts of the cold part were created from ABS material using 3D printing.

The figure 9 shows the detailed operation of the new extruder. the loader rotates using a Maltese cross system or Geneva drive. It is a gear mechanism that translates a continuous rotation movement into intermittent rotary motion. The rotating drive wheel is usually equipped with a pin that reaches into a slot located in the other wheel (driven wheel) that advances it by one step at a time. The drive wheel also has an elevated circular blocking disc that "locks" the rotating driven wheel in position between steps. Because the mechanism needs to be well lubricated, it is often enclosed in an oil capsule.

Conclusion And Prospects

The objective of this paper was to redesign a new type of ceramic-paste extruder system able to print bulky ceramic prostheses such as the human hip. It is based on the plunger extrusion mechanism of a paste extruder and can easily be adapted to other low-cost 3D machines, which extends the access of this technology to a larger number of designers. To do this, the first aim of this work is to evaluate and improve different concepts and to choose the best one among them. The second goal of the present work was to construct a visual prototype of the extrusion head to communicate both abstract and concrete ideas and to establish monetary values for comparison to the original design. It was very limited when printing voluminous parts because this task was impossible without stopping the printing process in order to refill the barrel, which was negatively reflected in the quality of the final product. Then, the design challenge was to satisfy this main function while combining the maximum performance criteria, mainly quality, adaptability and flexibility, the diversification of materials to be deposited, productivity and to have a competitive product compared to these similar products.

The decision matrix method or Pugh's method allowed the evaluation and improvement the different concepts, and helps to choose among six extruder concepts derived from the extruder system for BCN 3D that will lead to an innovative extrusion head were generated by means of a Morphological Matrix in our previous work, which one will give priority. The concept chosen relate to an automatic syringe storage extruder system. It adopts three subsystems. The automatic syringe loading system, which is operational to manually receive several syringes of the same or different volumes, allows the syringe feeding system to be loaded and unloaded once the syringe is empty. The syringes are automatically transferred to the holding system using an arm. The holding system allows the fixing of the syringe in order to perform printing with ceramic material. Thereafter, the finalization and analyzation of the best concept with the use the kinematic diagram and 3D-CAD environment to show the basic structure of the new extruder system was made.

In future works, the execution of the 3D Design of the extruder and selection of the appropriate materials will be performed for each element, followed by the dimensioning and tolerancing phases. This process includes the affectation of GDT (Geometric dimensioning and tolerancing) and surface roughness and also the calculation of parameters, such as forces, loads, pressure, etc. Then, a prototype of the designed extruder 3D will be manufactured and validated with experimental tests. Finally, the possibility of hybridization of this ceramic paste extruder with that of based on the extrusion of plastic filament (FDM) inside the same machine will be investigated.

Declarations

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Tables

See **Table 1** in the supplementary files.

Table 2.

The most important specifications for designing the new head extrusion system.

Function	Definition
Volume	It is the volume of the printed parts which has an impact on the dimensions of the syringe used for printing. The extruder should print small as well as large parts
Counter space	The size of the extrusion system that must necessarily be respected to install it on the BCN3D printer machine
Energy	The energy source used for the extrusion system to work in the best conditions
Continuous working time	The extrusion system must print continuously whether it is small or large parts
Adjustment time	The time required to make adjustments or to change the empty syringe with another one filled with a ceramic material to print continuously
Innovative solution	Our solution must certainly be innovative and optimize
Fixing time	The time required for loading and unloading the syringe

Table 3.

The concept screening matrix-first iteration.

Selection criteria	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Volume	+	+	+	+	
Counter space	-	+	-	-	
Continuous working time	S	+	+	+	
Adjustment time	S	+	+	+	
Innovative solution	+	S	+	-	
Energy	S	S	S	-	
Fixing time	+	+	+	+	DATUM
Sum +'s	3	5	5	4	
Sum -'s	1	S	1	3	
Sum S's	3	2	1	0	
Net score	2	5	6	1	
Rank	3	2	1	4	
	Consider	Consider	Consider	Dead-end	

Table 4.

The concept screening matrix-second iteration.

Selection criteria	Concept 1	Concept 2	Concept 3	Concept 6
Volume	-	S		+
Counter space	S	S		S
Continuous working time	-	S		S
Adjustment time	-	-		S
Innovative solution	S	-		S
Energy	S	S		S
Fixing time	S	-	DATUM	S
Sum +'s	0	0		1
Sum -'s	3	3		0
Sum S's	4	4		6
Net score	-3	-3		1
Rank	2	2		1
	Dead-end	Dead-end		Consider

Figures

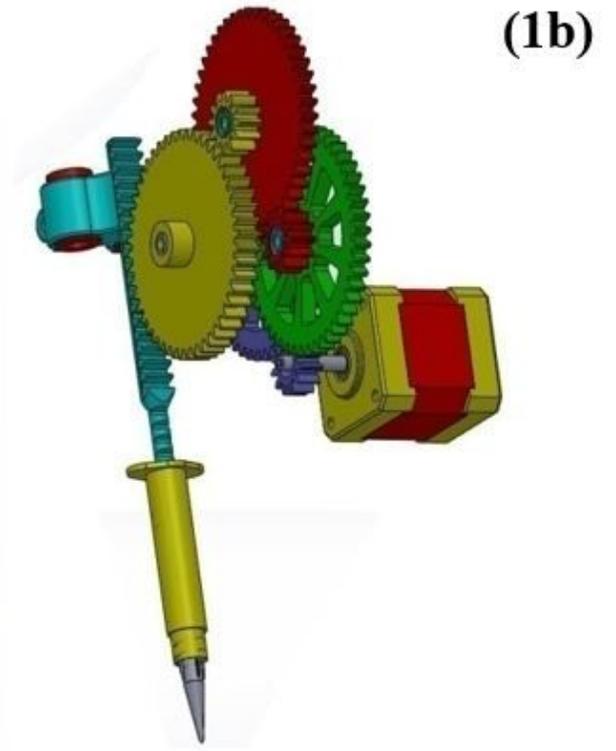
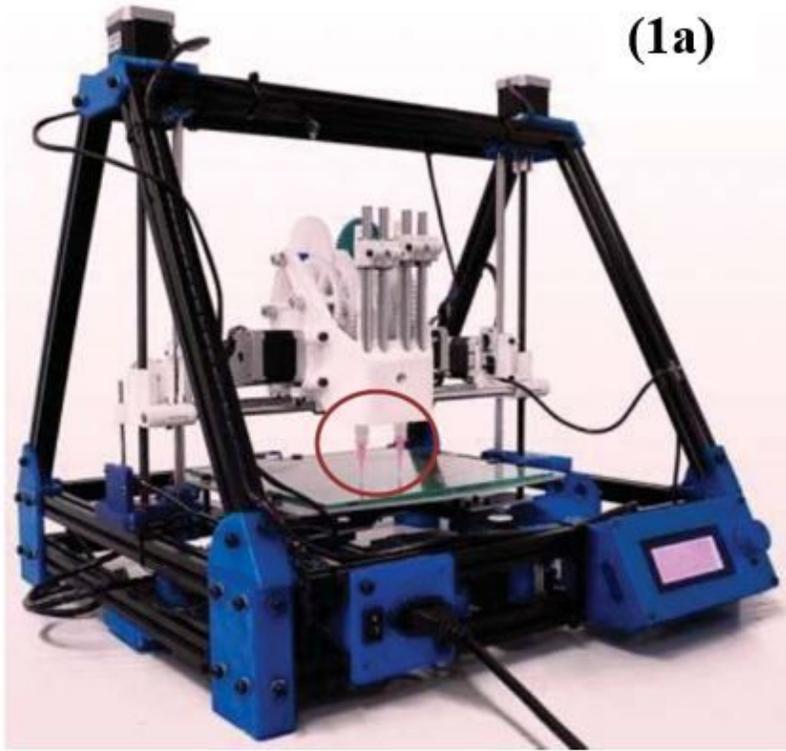


Figure 1

BCN 3D ceramic printer (1a). Detail of the printer (1b)

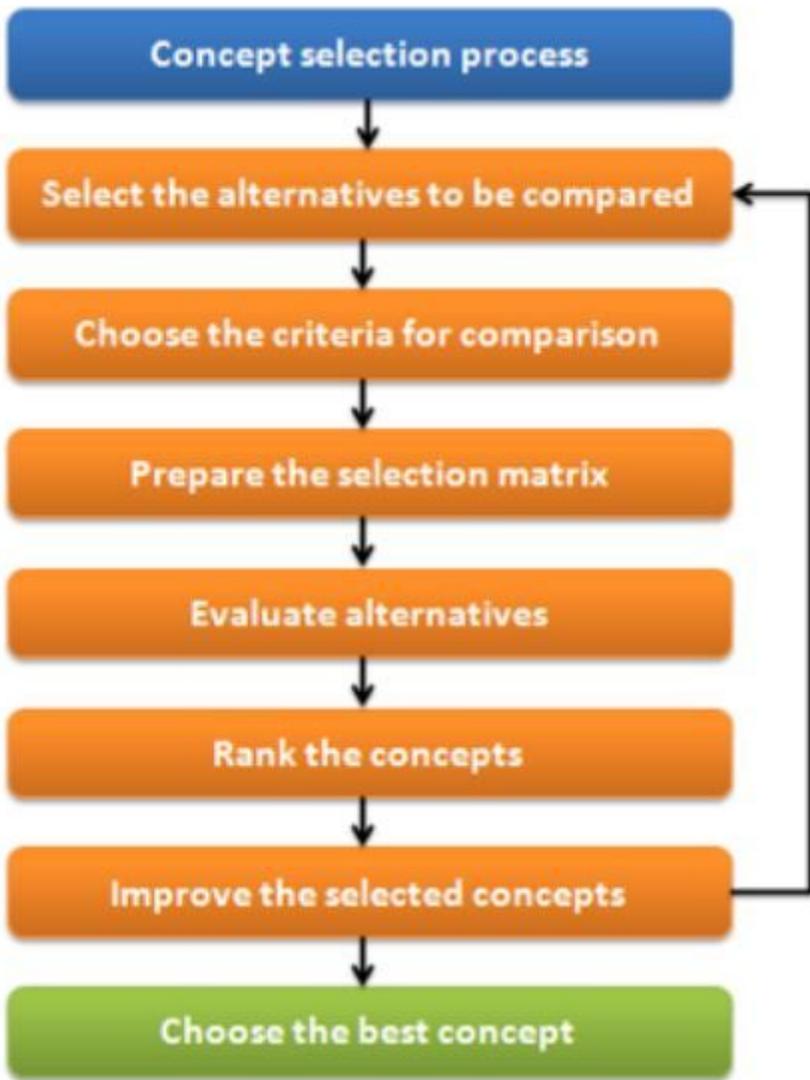


Figure 2

Decision matrix flow chart

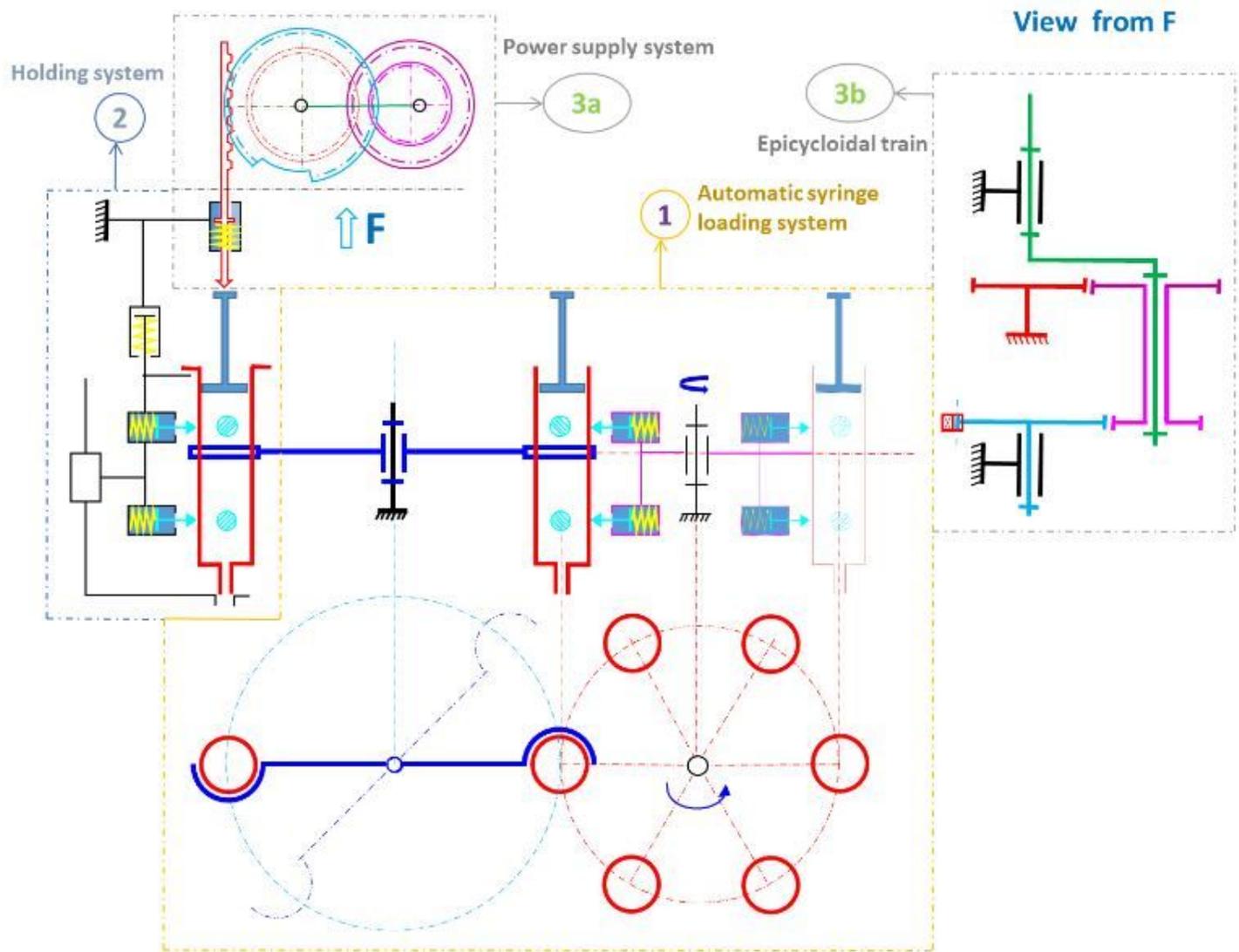


Figure 3

The kinematic diagram of the new extruder mechanism

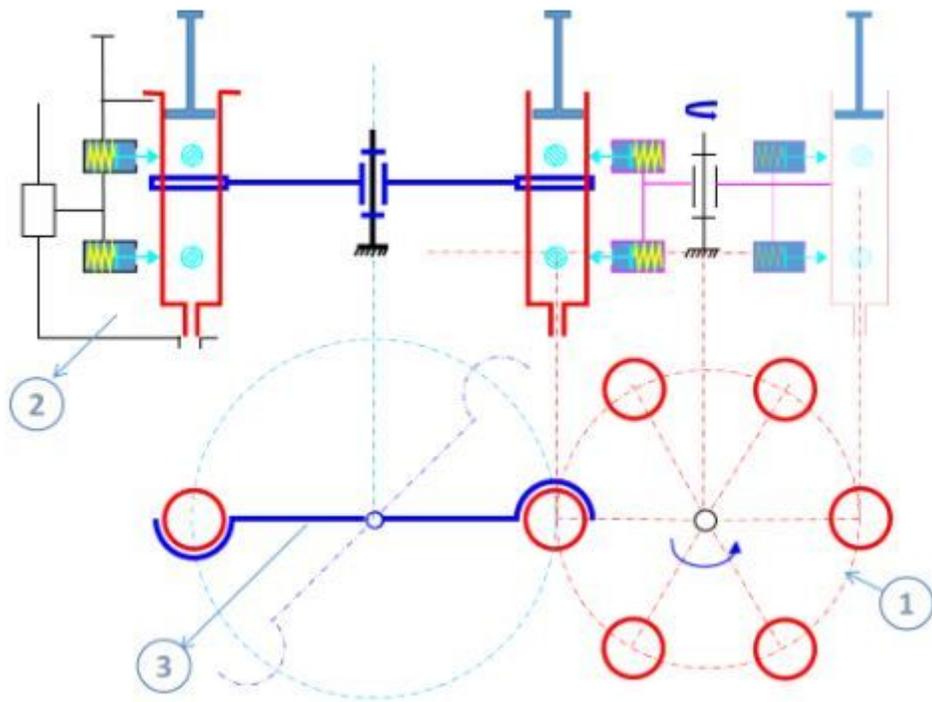


Figure 4

The automatic syringe loading system

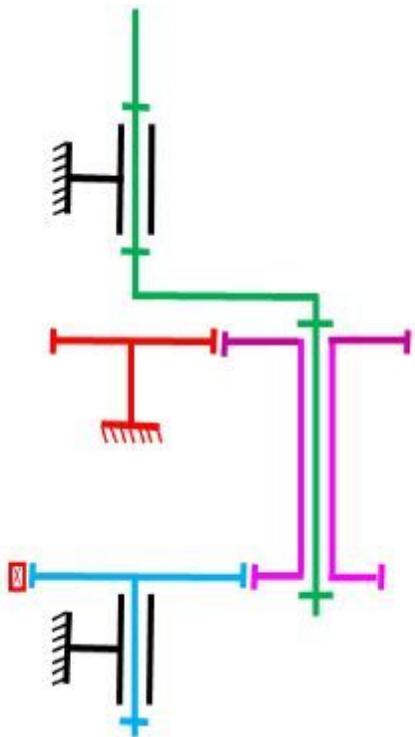


Figure 5

The transmission system

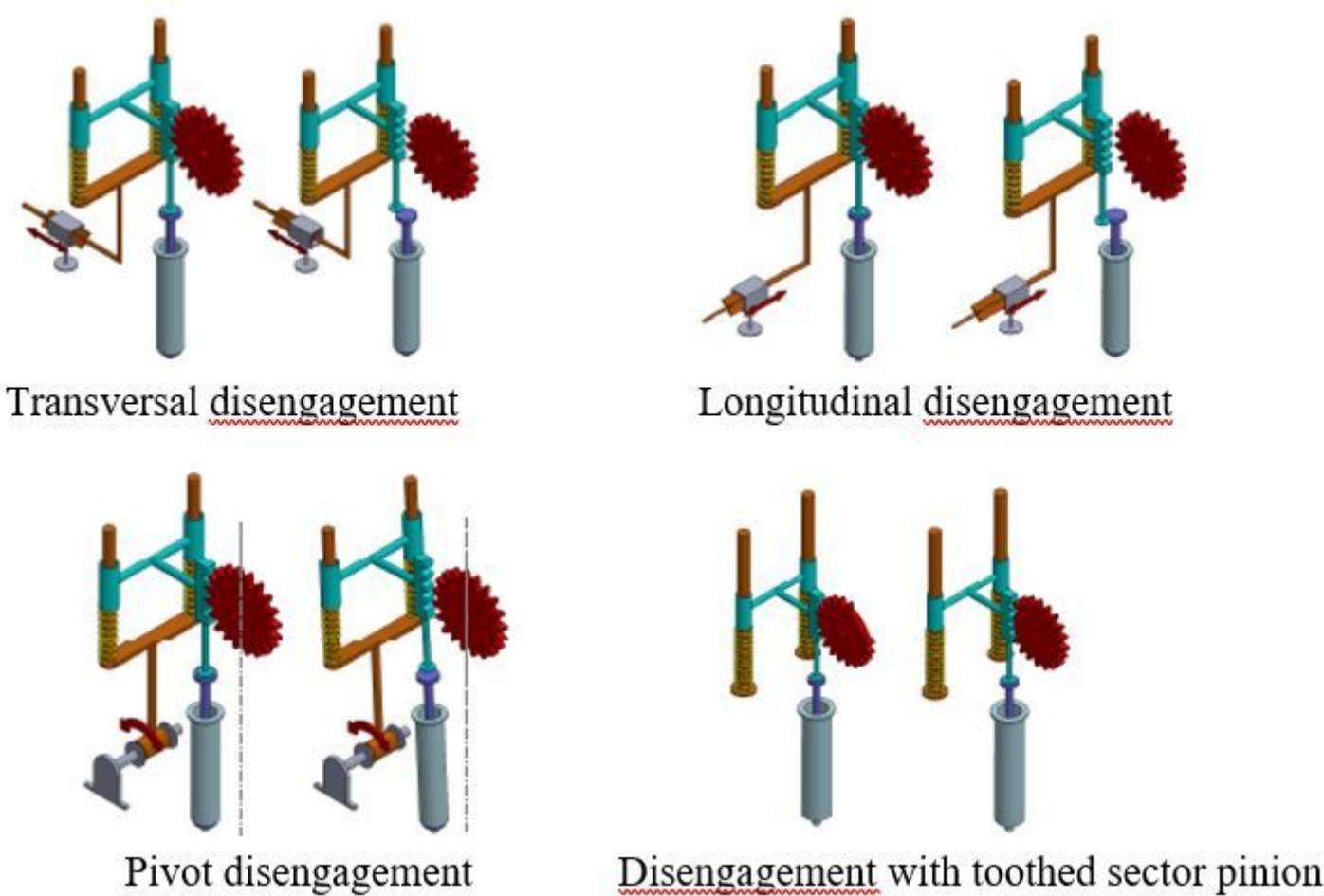


Figure 6

Ways of extraction of the syringe

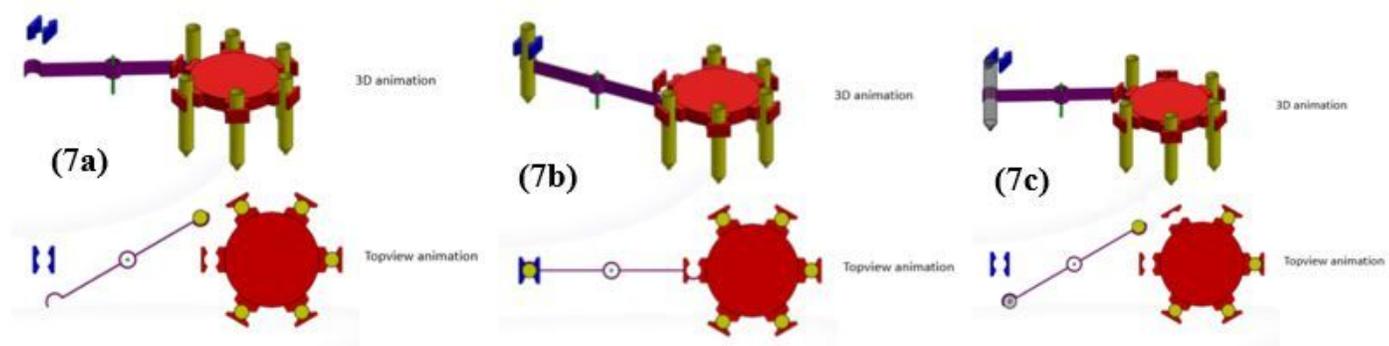


Figure 7

Different position to load and unload the syringes

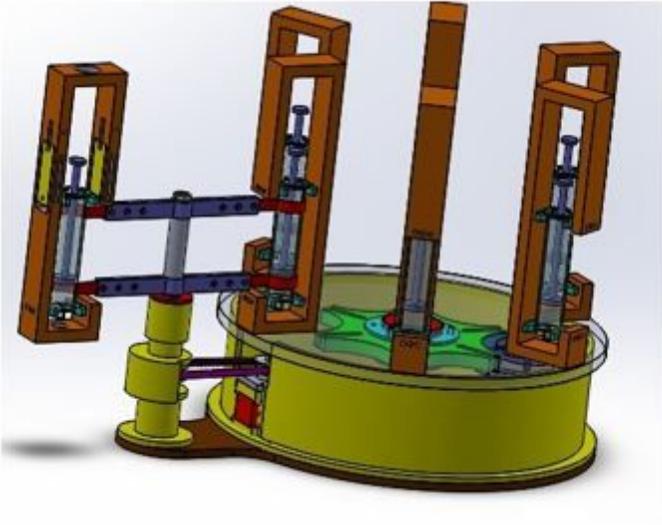


Figure 8

CAD model of the second concept of dual extruder head

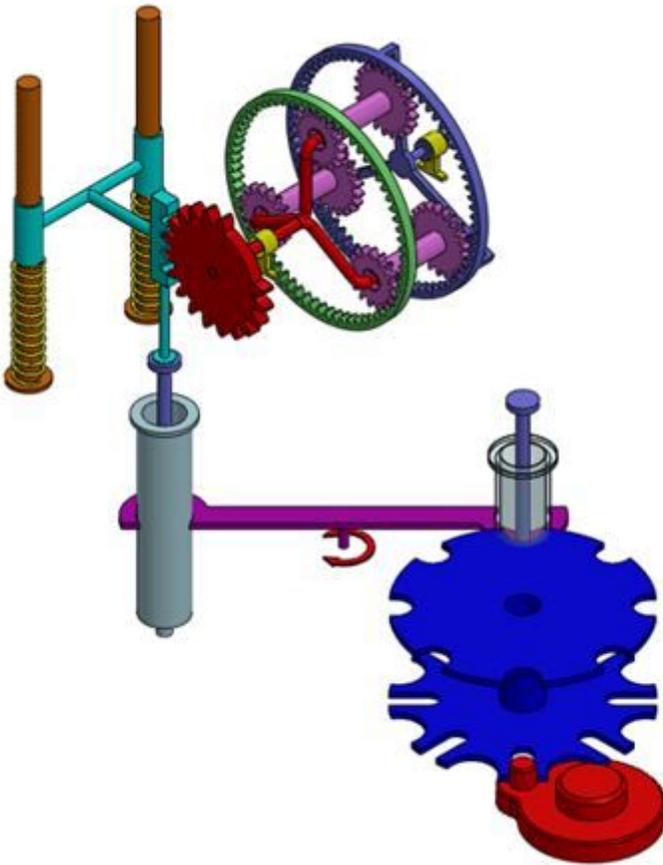


Figure 9

Detailed operation of the new extruder

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [TABLE1.docx](#)