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Development of a 3D printer optimized for rapid prototyping with continuous fiber fabrication technology

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Abstract. In the industrial field, Additive Manufacturing is a production concept that is increasingly gaining ground. The secret of its success lies in its definition: being able to produce an object by the progressive deposition of material instead of its removal as for the traditional machining. In this way, problems such as waste quantities, complex geometries and machining changes are greatly reduced, making these processes particularly useful and effective for rapid prototyping and the production of small series of objects. This experimental work examines the changes made to a 3D printer initially set up for the use of polymeric materials with Fused Deposition Modelling technology. Going into more detail, this machine was modified in a manner that would make it compatible with the introduction of polymer filaments reinforced with continuous carbon fiber according to the main principles of Continuous Fiber Fabrication technology. The changes made also involved electronics and informatics so that the printer could be easily operated through the platform.

Introduction

Additive Manufacturing (AM) is currently the most ground-breaking manufacturing technology capable, at least potentially, of changing traditional manufacturing paradigms. Revolutionary is the idea of considering objects as a superposition of a number of sections of extremely limited thickness. Exploiting this concept, it is possible to obtain the desired piece by depositing a series of layers of certain materials (typically thermoplastic polymer-based) using appropriate devices [1,2]. Specifically for this reason, AM contrasts with classical production methods based on plastic deformation of the material, such as molding, or centred on the removal of material, as in the case of turning and milling [2].

The development of AM has already reached such a level that it can be used in several industrial sectors (including aerospace, automotive, robotics, biomedical industry) [3,4,5], and its progress is expected to continue in the future, allowing it to become even more widespread [6].

AM is compatible with various types of materials, although the most widely used are undoubtedly thermoplastic polymers, e.g. polyamide (PA), polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) and polyether-ether-ketone (PEEK). In fact, this class defines a good compromise between ease of production, low cost, and mechanical performance of the manufactured product [7]. Frequently, these materials are used in the form of filaments, a characteristic that makes them suitable for certain additive manufacturing processes such as, for example, Fused Deposition Modelling (FDM), also known as Fused Filament Fabrication (FFF) [8].

An evolution of this manufacturing process has involved the introduction of reinforcements within the filament to increase the overall performance of polymers [9]. In this way, the structures obtained combine stiffness, toughness with light weight and corrosion resistance properties [10], aspects that make them highly coveted in sectors like prototyping or production of small series objects (e.g., in the automotive and biomedical fields).

The most widespread AM technology for these composite materials is certainly Continuous Fibre Fabrication (CFF), in which thermoplastic filaments containing carbon (but also glass or Kevlar) reinforcement in the form of short (SF) or continuous fibres (CF) are used [11,12]. This technology has experienced significant growth in the last few years since it is only from 2015 that several companies started to develop systems to process thermoplastic polymers reinforced with carbon fibres. Some of these devices are based on fibre deposition using 6-DOF robotic arms (e.g., Continuous Composites, Moi Composites), but most of the proposed systems involve the use of desktop 3D printers (e.g., Markforged, Anisoprint, Desktop Metal) [13].

Certainly, the degree of complexity of CFF technology is higher compared to FFF for neat-thermoplastic polymers since the composite has several elements, each of which has its own physical properties. Moreover, unlike traditional manufacturing technologies for composites in which strength and orthotropy characteristics are imparted to the part based on the weave of the reinforcing fabric, in CFF these are strictly dependent on the process set-up, particularly the deposition mode adopted and the orientation imposed on the fiber on each subsequent layer [11,12].

The high potential of this new composite manufacturing technology has also attracted the research community in recent years. To date, there are several studies on 3D-printed composites in the literature, most of which report mechanical characterizations of composites made with commercial 3D printers (generally, as a function of printing parameters) [11,14,15]. However, it is evident that most of the criticalities highlighted are related to hardware and software limitations of commercial printers. In this context, as there have only recently been significant developments in this field, the literature on 3D printing of carbon fibre composites still lacks information and does not offer solutions on aspects that are crucial to definitely improve the quality of printed parts [16].

Based on the above, this paper summarises the modifications made to a commercial CubePro Duo 3D printer by 3D System, originally designed for rapid prototyping of pure polymer parts, to make it suitable to process polymer filaments reinforced with both short and continuous carbon fibres. The scope of the modification is indeed to allow the use of commercial reinforced filaments (in particular, Onyx and CFR filaments traded by Markforged) by means of a device that is improved in terms of process conditions (e.g., heating of chamber) and software flexibility.

3D printer set up for neat polymer and short-fibre reinforced filaments

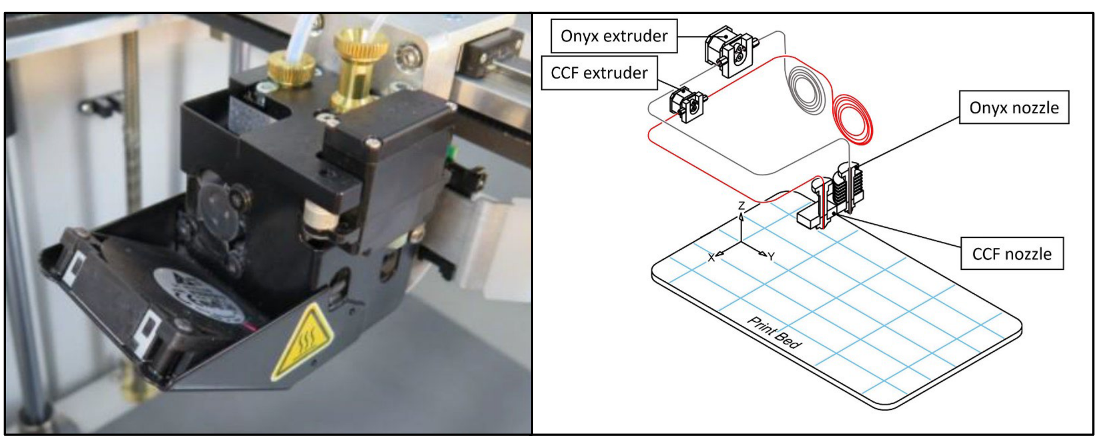
The transformation process described in this paper considered a CubePro Duo™ (3D Systems, Rock Hill, SC, USA), an Additive Manufacturing 3D printer based on the principles of Fused Filament Fabrication. It is a closed-chamber machine with an overall build envelope of 578mm x 578mm x 591mm, capable of producing parts with two different polymer materials. From a kinematic point of view, this printer falls into the Cartesian category as it operates along the three Cartesian axes X, Y and Z. Specifically, the horizontal movements in the X-Y plane are carried out by stepper motors which move the extrusion head by means of a toothed belt drive, while the vertical movements (along the Z axis) are performed by the glass printing plate through a threaded rod. Consequently, the print volume of the machine is limited both by the size of the printing plate (275 mm x 265 mm) and by the maximum vertical excursion allowed (230 mm). One of the strengths of this printer is undoubtedly the heating of the internal chamber using a heater that can raise the internal temperature to ~70°C. In fact, this feature leads to a considerable improvement in performance, as working in a heated environment reduces the effects of warping, an anaesthetic printing defect that causes strains due to uncontrolled cooling and excessive temperature changes to which the newly melted material is subjected. In addition, internal heating improves the quality of adhesion between subsequent layers of the workpiece [18,19].

The CubePro Duo is a machine with a certain flexibility, especially in terms the materials that can be used. Depending on the requirements and the final characteristics of the part to be produced, it is indeed possible to choose the most suitable filament from polyamide (PA), polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS). However, the range of materials that can be used does not include composites. For this reason, given the scope of this work, it was necessary to replace the printhead with one able to process fibre-reinforced polymer filaments regardless of the fiber length (short or continuous). Specifically, the filaments to be introduced are Onyx and CFR, both traded by Markforged, whose main properties are listed in Table 1.

Table 1 Material properties of filaments by Markforged Inc [17].

Property	**CFR**	**Onyx**
Density [g/cm^3]	1,4	1,2
Tensile Strength [MPa]	800	40
Tensile Modulus [GPa]	60	2,4
Flexural Strength [MPa]	540	71
Flexural Modulus [GPa]	51	3,0
Compressive Strength [MPa]	420	N/A
Compressive Modulus [MPa]	62	N/A
Izod Impact-notched [J/m]	960	330
Heat Deflection Temp [°C]	105	145

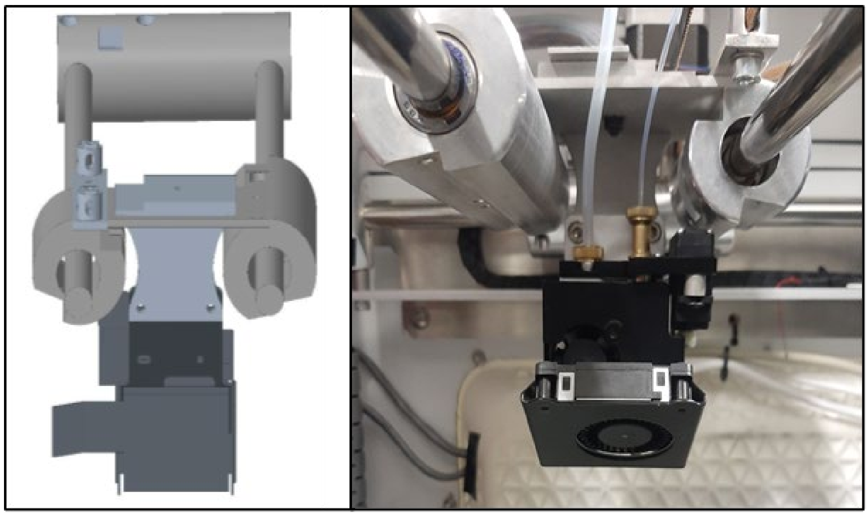
The choice therefore fell on a Mark Two model (Markforged® Inc., Watertown, MA, USA), a head technology that represents the latest updated version of the most diffused commercial desktop printer for CF-reinforced composites (Fig. 1a).



a) b)

Fig. 1 Markforged® Mark Two printhead: (a) specific view and (b) scheme of the printing structure.

Obviously, although it has managed to retain the Cartesian structure of the machine (Fig. 1b), the replacement of this latter device has required inevitable changes to the structure of the movable crossbar on which the extrusion head is fixed. In fact, due to different geometry of the original and new extrusion heads, it was necessary to design the support entirely, the final rendering of which is illustrated in Fig. 2. The solution adopted makes possible the exploitation of the space between the two sleeves of the moving crossbar in such a way as to limit as much as possible the overall dimension in the vertical direction, with limited repercussions on the size of the print volume.



a) b)

Fig. 2 New printhead fixing system: (a) CAD view and (b) specific view

Another aspect to consider is the positioning of the stepper motors that manage the filament feed since, contrary to the original layout of CubePro Duo, the extruders cannot be fixed directly on the printhead. As a result, the consequent reduction in volume and weight of the printhead makes it possible to reduce the inertial mass terms with obvious advantages, particularly, in terms of maximum values assumed by accelerations and jerks. This results in a reduction in printing times, especially those related to stages where there are no limits imposed by the filament printing parameters.

Obviously, all these advantages were only gained after having defined a new position for the extruders inside the printer. A convenient location must be selected to guarantee for periodic maintenance of the motor, and, at the same time, not to create any impediments to the movements of the printhead. Among the various solutions considered, it was decided to install these electrical devices on a support to be designed and inserted in place of a portion of the upper case of the CubePro Duo. In addition, this layout ensures a short path between the printhead and the actual extruders, significantly reducing problems associated with filament jamming inside the polytetrafluoroethylene (PTFE) tubes that connect the two components.

The proposed support roof cover (represented in red in Fig. 3a) envisages a profile obtained by thermoforming and able to lead to an increase in the internal chamber due to the genesis of a new internal compartment in which the extruders are placed and fixed through a bolted joint (Fig. 3b).

a) b)

Fig. 3 New roof cover design: (a) CAD external view and (b) extruder fixing seat

As visible in Fig. 3b, the increase in volume of the inner chamber affects only the front portion of the machine. This decision was made to limit the increase in chamber volume as much as possible. Indeed, being located above the printhead, this portion of space is not part of the print volume. Moreover, an excessive volumetric increase could have been detrimental from a thermal standpoint, leading to both a lengthening of the chamber heating time and a slight decrease in the maximum temperature reached inside it.

It is worth noting that a support cover with such a profile was also advantageous because it provided sufficient space behind the extruder compartment to be able to attach the spool holders. In addition, this location makes replacement of the spools very easy and fast, and limits the distance travelled by filaments to reach the extruders.

Electronic and IT operations carried out on the 3D printer

The modified printer is able to properly move the head within the printing volume. Therefore, attention then turned to the electronics of the system, particularly the motherboard. In fact, the original motherboard of the CubePro Duo has some criticalities, among which it is worth noting the impossibility of implementation with auxiliary boards and its incompatibility with the newly introduced printhead.

A new motherboard was therefore needed to solve all the problems encountered. The choice fell on an MB6HC model from the Duet 3 series, a next-generation control board that can be used with a wide range of machines, including 3D printers, CNCs, laser cutters and other devices. The main goal of the Duet 3 series is to achieve maximum flexibility in machine design through high-capacity motherboards, expansion boards, and custom expansion modules. Configuration flexibility and advanced functionality are provided by the RepRapFirmware running on the motherboard and the DuetSoftwareFramework running instead on a Single Board Computer (SBC; in this case, a Raspberry Pi 4). The overall hardware requirements and the operating limits of the MB6HC are compatible with the equipment on the modified CubePro [20]. In addition, not all connectors on the board are used so that there are free terminals useful for future insertion of other devices (e.g., insertion of LED strips or platter heaters).

Once the motherboard was properly introduced, attention turned to the inclusion of the Raspberry Pi 4, i.e., an SBC with which to implement the performance of the Duet 3 MB6HC. In fact, this addition offers several advantages, including higher network transfer speeds, support for plug-ins that require more than the RepRapFirmware present on the Duet Web Control (DWC) platform, and the ability to connect devices such as screens with HDMI ports, keyboards, mouse, and USB flash drives. As one can imagine, these two new electronic components cannot be placed in the place where the old motherboard originally was. Hence, it was decided to place both devices inside a compartment on the right side of the printer, already equipped with brackets for attachment (Fig. 4).

Both case and relative cover were made of polylactic acid (PLA) and were fabricated additively

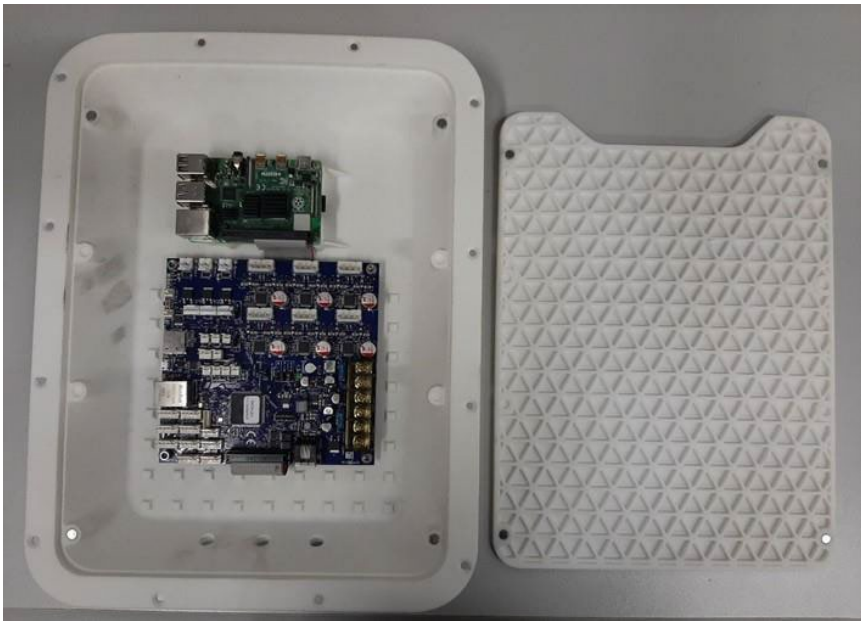


Fig. 4 Side case containing Duet 3 motherboard and Raspberry Pi 4.

by Selective Laser Sintering (SLS) technology. A series of side holes were made for the passage of cables. To protect the electronic devices placed inside this compartment, the support is fitted with a cover with four magnets to ensure the compartment is closed properly. This prevents any short circuits due to unwanted contact of the back of the board with the backing plate.

Once the new board was installed, the focus was on the various electrical connections to be made with all the electronic components of the modified CubePro Duo. It was then sufficient to connect the components (i.e., nozzles, extruders, stepper motors, and limit switches) with the MB6HC of the Duet 3D following the wiring diagram provided by the motherboard producer [21].

It is worth noting that during the wiring phase of the machine, a series of technical problems arose, then completely solved. Among these, it is worth to mentioning those relating to the connections of the SBC with all the interface devices required to guarantee the correct operation of the CubePro Duo. In fact, the Raspberry Pi 4 has four USB ports that under normal printer operating conditions cannot be used as they are located inside the chamber described before. Therefore, disregarding the inconvenient hypothesis of redesigning the electronic compartment, it was decided to reuse the original slot working in two ways depending on the device to be connected. As regards the interface devices with the Raspberry and the interface platform (mouse and keyboard), it was decided to use Bluetooth wireless devices, as this leads to the advantage of having no connecting cables but only small receivers that can be easily plugged in before the machine is switched on.

Obviously, the solution just described was not feasible for connection with a USB mobile unit (necessary for the introduction of the CAD files of the object to be printed) due to obvious difficulties in inserting the unit under normal operating conditions. This led to the need to use USB ports originally found on the external surface of the CubePro Duo, a requirement that was solved by designing an extension cable compatible with the Raspberry's USB ports, of sufficient length to reach the CubePro’s side sockets. For this application, four-core Belden cables with twisted wires were used: together with the external shielding layer, this solution makes it possible to reduce electrical noise, thus providing a stable signal that is little affected by the presence of other electrical equipment placed nearby.

Given the positive result achieved, this approach was also used for the other connections to the external environment, namely the network cable and the HDMI video cable for the screen. However, unlike the USB sockets, the CubePro does not have a designated location for such connections to the outside environment. For this reason, it was opted to install a plate with the appropriate modules (e.g., RJ45 and HDMI sockets) near the compartment for the SBC.

Once the phase of wiring all the electronics was finished, the firmware for the motherboard (called RepRapFirmware) was configured. Specifically, this stage involves writing (also with the help of appropriate programs) the configuration files used to define the operating and functional conditions of the printer (such as defining print volume limits) and all the electronic devices of the machine (e.g., stepper motors, heaters, limit switches, temperature sensors).

3D printer set up for continuous-fibre reinforced filaments

Firmware installed on the Duet 3 motherboard ensures that the printer will operate properly with filaments made of pure polymer or, at the limit, reinforced with short fibres (e.g., Onyx filament), but, in this base condition, it still does not allow the use of Continuous Fibre Reinforced (CFR) filaments. This limitation is imposed by the conditions under which the newly deposited material detaches from the filament still contained in the hotend nozzle when the filament feed is interrupted. Under these conditions, detachment occurs independently only if the fibres contained in the filament are short. In contrast, when CFR filaments are used, the separation process is prevented by the fibre itself, which, being unaffected by heating, remains continuous. Therefore, in this case, the filament separation must be achieved by a cutting operation performed by a servomotor fixed on the printhead. This additional operation therefore required writing a special macro in the firmware that will manage the activation of the servomotor whenever it is necessary to cut the CFR filament (typically, between one deposited layer and the next).

At this stage the printer can execute all operations and can be switched on to carry out the preliminary printing tests, based on which to adjust the process parameters and optimize printing. Therefore, the first printing tests were focused on the generation of increasingly complex flat figures using only Onyx filament (Fig. 5), to obtain feedback on the good coordination of the movement systems along the X and Y axes. The execution of this initial work has made it possible to solve some typical problems at the start of printing, such as, for example, the height of the first layer, which is critical due to aspects relating to the correct adhesion of the extruded material to the printing plate, and the correction of the extrusion factor to obtain a correct filling of the printed figures without excess material.

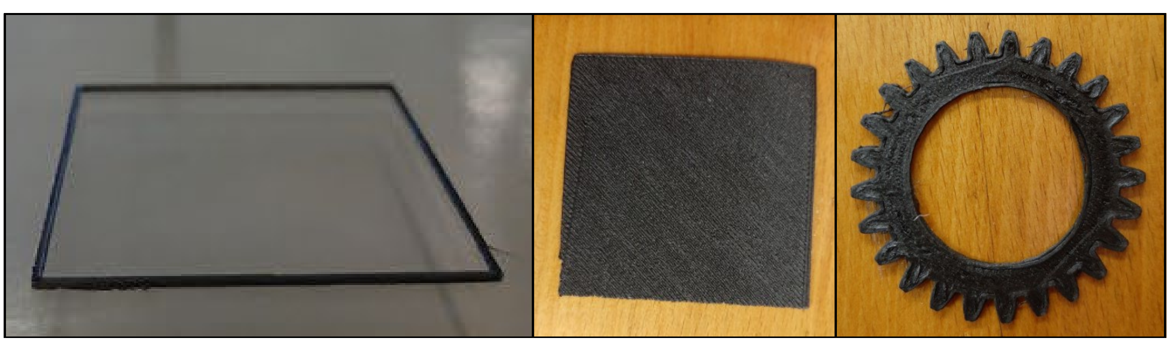


Fig. 5 First 2D objects obtained with printer converted to Continuous Fibre Fabrication (CFF) technology

Then, having completed the optimisation of 2D figures, the first attempts at the genesis of 3D objects were carried out, also employing continuous carbon fibre in the filling stages. As an example, Fig. 6 shows a series of specimens prepared for tensile tests in full compliance with the ISO standard valid for composite materials [22].

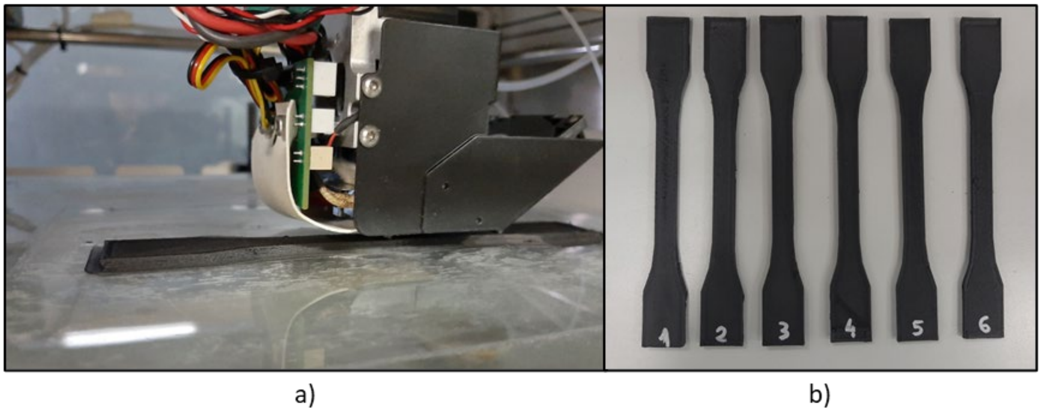


Fig. 6 3D printing process of a tensile test samples (a) and a comparison of the different parts produced (b)

The final parts thus obtained met all the dimensional tolerances of the standard with maximum deviations from the nominal value within 0.2 mm. Furthermore, as can be seen in Fig. 6, the surface finish of the parts thus obtained was satisfactory and comparable to those found in the literature [23].

Conclusions

The experience described in this paper was aimed at converting a 3D printer based on FDM technology to the use of commercial composite filaments with short or continuous carbon fibre reinforcements (Onyx and CFR, respectively). The conversion process needed both various modifications to the original printer's components and implementation with dedicated components (e.g., the replacement of the printhead with a Mark Two by Markforged). In parallel with this stage of re-building, the printer's informatics was also updated by introducing a new motherboard with enhanced performance than the original one. This device also made it possible to connect a Single Board Computer, a Raspberry Pi 4, that improved and simplified the machine's work management.

Attention was then turned to the electronics (e.g., complete re-wiring of the machine), and to the machine programming, through which all the codes necessary to ensure proper operations with reinforced filaments were written. The final phase of the conversion process was the setting up of the device, which involved calibration steps (heaters and stepper motors), movement tests, and extrusion tests. Tables 2-3 summarise the main technical operating specifications of the converted 3D printer.

Table 2 Main technical specifications of CubePro Duo modified with Mark Two printhead.

Parameter	**3D printer**
Technology	Continuous Fiber Fabrication (CFF)
Printer dimensions [mm]	578 (w) x 578 (l) x 591 (h)
Maximum build size [mm]	242,9 (w) x 270,4 (l) x 230 (h)
Z axis resolution [mm]	0,10
Chamber heating	Yes, up to 70°C
Bed heating	No

Table 3 Main printing features of CubePro Duo modified with Mark Two printhead.

Parameter	CFR	Onyx
Filament diameter [mm]	0,35	1,75
Extrusion temperature [°C]	270	265
Extrusion feed rate [mm/min]	600	1200
Filament drying	Recommended	Recommended
Nozzle diameter [mm]	0,35	0,40
Layer thickness [mm]	0,15	0,15

At this stage, the modified 3D printer can work with both short and continuous carbon fibre-reinforced filaments, under process conditions comparable with those of a Mark Two commercial printer. It is noteworthy that, unlike the latter, the implementation of the heating system in the chamber, based on some preliminary tests, is proving its effectiveness in limiting deformations of the produced part (due to lower thermal gradients between cooled deposit and fused filament), and should also improve adhesion between successive layers.

Certainly, this result leaves wide space to further optimization, and is to be considered as a starting point for future developments inherent to technological, process, and final product aspects, most of which, at the time of writing, are already under investigation (for example, the implantation with a heated printing bed to further improve the printed product's quality).

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