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Article

Filament Advance Detection Sensor for Fused Deposition Modelling 3D Printers

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Abstract: The main purpose of this paper is to present a system to detect extrusion failures in Fused Deposition Modelling (FDM) 3D printers by sensing that the filament is moving forward properly. After several years using these kind of machines, authors detected that there is not any system to detect the main problem in FDM machines. Authors thought in different sensors and used the Weighted Objectives Method, one of the most common evaluation methods, for comparing design concepts based on an overall value per design concept. Taking into account the obtained scores of each specification, the best choice for this work is the optical encoder. Once the sensor is chosen, it is necessary to design de part where it will be installed without interfering with the normal function of the machine. To do it, photogrammetry scanning methodology was employed. The developed device perfectly detects the advance of the filament without affecting the normal operation of the machine. Also, it is achieved the primary objective of the system, avoiding loss of material, energy and mechanical wear, keeping the premise of making a low-cost product that does not significantly increase the cost of the machine. This development has made it possible to use the printer with remains coil filament, which were not spent because they were not sufficient to complete an impression and also printing models in two colours with only one extruder.

Keywords: rapid prototyping; fused deposition; filament jams; extrusion failures; photogrammetry; manufacturing system

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1. Introduction

Nowadays, the use of 3D printers has extended beyond the research laboratories. It is possible to find them, more and more frequently, in houses, where it is used by a non-technical user; or in factories, where an error in the operation can suppose great losses [1]. Therefore, these machines must remain 100% reliable with near zero failed prints due to mechanical and electro-mechanical malfunctions.

After several years of development and improvement, the most important failure has not been corrected, the jams in the extruder. Some researches and engineers have optimized the grip force on 3D printer filament and even have developed novel feeding mechanisms [2-3]. This extrusion problem occurs to FDM 3D printers when the filament does not move as it is desired, and may be due to damage, stress, dust and small debris in filament. Nevertheless, the most common problems arise from a wrong filament diameter, a braking of the filament, or simply that the filament coil is over. In these cases, the printer keeps on moving but it does not deposit any material [4].

Although manufacturers and researches are constantly improving polymers manufacturing process, including fiber spinning and injection molding, the product quality and production efficiency is influenced by multiple processing and material parameters, such as the nominal shear and shear history, process temperature or long chain branching, mechanisms that currently are not completely understood. The control and optimization of such operations contribute to get closer and closer to the nominal filament size but it still moves in fairly large tolerances [3], [5–7].

In this paper, we present a development to detect all these extrusion failures (may be a knot coil, an extruder jamming or simply that the filament coil is over) which is proposed detecting that the filament is carried forward properly. To reach this goal, it is initially thought of a mechanical switch that detects when the filament fails to move, but although it seems trivial to cases in which the filament breaks or runs out, it is more difficult to detect the correct advance. For this reason, we propose to use a rotation encoder driven by the movement of the filament. The printer should consult repeatedly, while printing, that the encoder is rotating and therefore the filament goes forward. In the event that no progress is detected, the machine will stop and offer the option to change the filament, reload it and continue printing with not having to discard the part.

2. Review of extruder-filament sensors used for current 3D printers

2.1 Mechanical sensor

Mechanical sensors have been widely implemented in 3D printers, majority of them use a mechanical button to stay on while filament is detected could easily detect filament end or breakage to stop the printing. It is possible to find some detection systems using mechanical filament breakage sensors, but this kind of systems does not solve the main problem, which is a filament jam, due to the state of the switch would not change.

2.2 Load cell sensor

As the extruder feeds the filament to the hot end, the extruder is effectively pushing against the filament causing the extruder to apply extra load on the load cell. Load cells have strain gauges attached that change in electrical resistance when under different loads. This resistance change provides small voltage levels that can be amplified and then read by an analogue to digital converter. Unfortunately, load cell sensor could make it difficult to calibrate without a suitable weighing platform and stand.

2.3 Rotary encoder

A rotary encoder, is an electro-mechanical device that converts the angular position or motion of a shaft or axle to an analog or digital code [8]. There are two main types: absolute and incremental. The output of absolute encoders indicates the current position of the shaft, making them angle transducers. The output of incremental encoders provides information about the motion of the shaft, which is typically further processed elsewhere into information such as speed, distance and position. Encoder may have mechanical problems due to the high accuracy that must be taken to fabricate them. Environmental pollution can be a source of interference in optical transmission. They are particularly sensitive to shock and vibration devices, and their operating temperature is limited by the presence of electronic components.

2.3.1 Mechanical encoder

Mechanical encoders have an axis that spins internally thus activating different pins depending on the direction of rotation and speed. Although this type of encoder firstly seems easy to use, the resistance of the rotation axis is not desired. It could increase the resistance of the filament feed and it could affect the proper operation of the extruder.

2.3.2 Optical encoder

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The principle of operation of an optical encoder is based on the so-called photo couplers. These are small chips consisting of a diode as a photo emitter and a transistor which performs the tasks of photoreceptor (see Figure 1). This element is responsible for detecting the presence/absence of light through a concentric axis, it is manufactured with slots that allow the light to go through the disc to obtain the final measure [9].

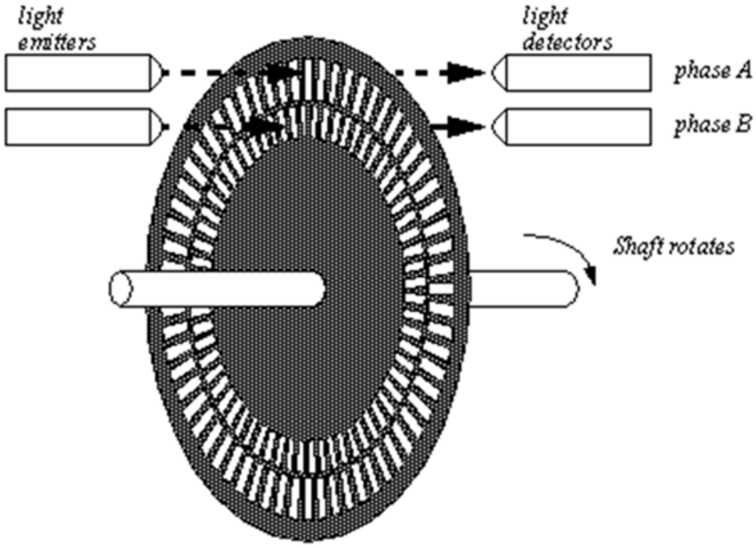

Figure 1. Principle of operation of an optical encoder

3. Filament auto-detection system development

3.1 Election of the sensor

The Weighted Objectives Method is one of the most common evaluation methods for comparing design concepts based on an overall value per design concept [10]. The biggest disadvantage of using other methods like the Datum method or the Harris profile is that the scores per criterion cannot be aggregated into an overall score of the design alternative. This makes a direct comparison of the design alternatives difficult. The Weighted Objectives Method does exactly this: it allows the scores of all criteria to be summed up into an overall value per design alternative.

The Weighted Objective Method assigns scores to the degree to which a design alternative satisfies a criterion. However, the criteria that are used to evaluate the design alternatives might differ in their importance. For example, the cost price can be of less importance than appealing aesthetics. The Weighted Objectives Method involves assigning weights to the different criteria. This allows the decision-maker to take into account the difference in importance between criteria.

The selected criteria and compared in Table 1 are the following:

E1. Filament detection (yes-no)
E2. Detecting the advance of the filament
E3. Not interference with normal movement of the filament
E4. Adaptability of the output signal
E5. Price
E6. Durability

Taking into account the scores (see Table 2), and as expected, the sensor that best meets the specifications is the optical encoder. In this work, an inexpensive bi-directional optical incremental encoder is used.

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Table 1. Filament detection sensor evaluation

Sensor	E1	E2	E3	E4	E5	E6	Amount	Compensation	Weight	%
E1	X	0,0	0,0	1,0	0,5	0,5	1,5	2,5	0,167	16,67
E2	1,0	X	0,5	0,5	0,5	0,5	2,5	3,5	0,233	23,33
E3	1,0	0,5	X	1,0	0,5	1,0	3,0	4,0	0,267	26,67
E4	0,0	0,5	0,0	X	0,5	0,0	1,0	2,0	0,133	13,33
E5	0,5	0,5	0,5	0,0	X	0,5	1,5	2,5	0,167	16,67
E6	0,5	0,5	0,0	1,0	0,5	X	2,5	3,5	0,233	23,33
Total							9,5	14,5	0,967	96,67

Table 2. Sensors marks

Sensor 1	Mark	Satisfaction	Final mark	Sensor 2	Mark	Satisfaction	Final mark
E1	16,67	100%	16,67	E1	16,67	100%	16,67
E2	23,33	0%	0,00	E2	23,33	100%	23,33
E3	26,67	100%	26,67	E3	26,67	25%	6,67
E4	13,33	100%	13,33	E4	13,33	75%	10,00
E5	16,67	100%	16,67	E5	13,33	75%	10,00
E6	23,33	75%	17,50	E6	16,67	75%	12,50
		Total	73,33			Total	79,17

Sensor 3	Mark	Satisfaction	Final mark
E1	16,67	100%	16,67
E2	23,33	100%	23,33
E3	26,67	100%	26,67
E4	13,33	75%	10,00
E5	13,33	75%	10,00
E6	16,67	50%	8,33
		Total	95,00

3.2 Hardware assembly

3.2.1 Assembly part design

Once the sensor is chosen, it is necessary to design the part where it will be installed. It must be taken into account that it cannot interfere with the normal function of the machine. To do it, we will employ photogrammetry scanning methodology since it will be possible to do it in a precise way [11]. This method uses reverse engineering thus allowing to reduce the costs of the development.

After taking numerous pictures of the object, they are processed using a computer software so that common points are identified on each image. A line of sight (or ray) can be constructed from the camera location to the point on the object. It is the intersection of these rays (triangulation) that/which determines the three-dimensional location of the point.

The result of the process is a digital tridimensional object which can be used as a model to design the rest of the parts. It is interesting to include graphic scales to get the correct dimensions of the digital model. Figure 2a shows a sample of a total of 74 images involved in the process.

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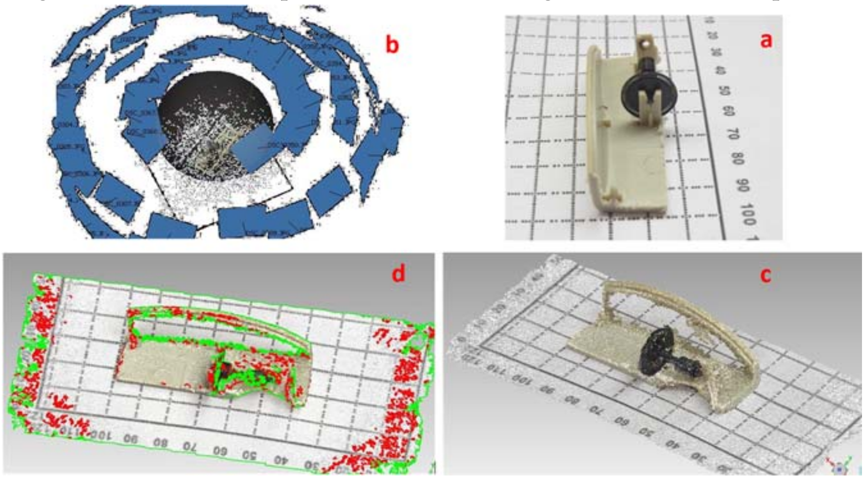

Figure 2. Images for photogrammetry process

The software locates the pictures and shapes a points cloud of the scanned object. The process is showed in Figure 2b and 2c where it is possible to see the pictures completely orientated and the formatted points cloud.

As it is possible to notice in Figure 2c, there are some defective parts. This is due to the brightness of the object, so it is necessary to perform a repair of the digital model, so it can be reached a model as similar to the real as possible. To achieve this, first of all a filter of the points is performed to remove the noise eliminating points spaced of the set a specified size. After this, different holes are detected. In this case a total of 698 of holes which 670 are closed automatically since have a small size. The remaining 28 holes are manually closed to keep the original form. An automatic reparation of errors is carried out, and finally, we get the digital solid model. Figure 2d shows an image of the process and the final model.

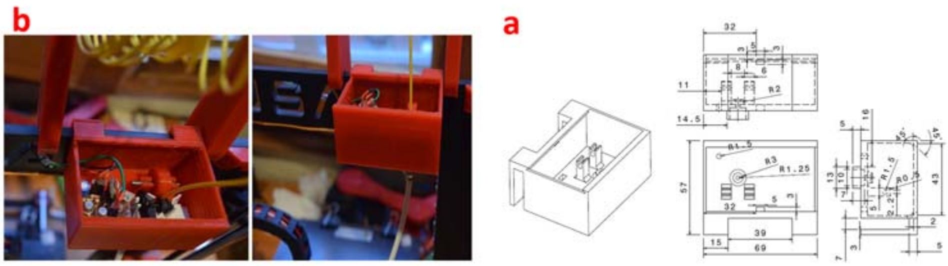

Figure 3. Dimensions and real product

Once the three-dimensional solid model is obtained, it is exported to a 3D design program for modeling the part where it will be assembled. In this way, it is possible avoid design errors that have to make too many times to iterate to find the optimal model. In Figure 3a and 3b the dimensions of the modeled part and the real product made with a 3D printer are showed.

3.2.2 System assembly

The whole system is installed on the top of the printer, so that the filament goes through the sensor. After the sensor. The filament is leaded through a Teflon tube to the hot-end, analogously to Bowden system.

After checking that the system does not interfere in the normal function of the machine, it is connected to the main electronic board of the printer (an Arduino Mega board).

3.2.3 Firmware modifications

Once the system is installed, it is necessary to modify the firmware of the machine, so it is possible to get the sensor signal and act accordingly. Since the encoder works asynchronously, it is necessary to use program interruptions to get the signal correctly. These interruptions will detect whether the filament is moving or is blocked. Moreover, it will be possible to calculate the speed at which the filament is advancing in order to be sure about the quantity of material deposited.

However, after repeated tests, it is observed that the interruptions take place very frequently, which interferes with the operation of the printer. That is why we finally choose for attending interruptions every 5 seconds, regardless when interruptions occur the rest of the time. After several tests, it is proposed that after ten seconds it will have produced at least one interrupt of the filament if it is proceeding correctly, and otherwise, ten seconds without detecting an interruption should be sufficient to stop printing due to an error in filament advancing. A new pause menu is also implemented, since error filament was not previously available.

Once an error in advancing filament is detected, the printer activates the implemented pause mode because filament error, from which you it is possible to load and unload the actual filament to continue printing avoiding to lose the piece.

4. Performance evaluations

4.1 Filament defects

Although most of filament producers for 3D machines are constantly developing and improving their products, the manufacturing method has so far prevented achieving a filament with a constant diameter. This excess in diameter is sometimes too much for the machine, causing bad finishing models, jamming of the extruder, or even it could damage the extruder. To check the filament diameter of different producers, 3 meter samples were taken, every centimeter of filament using a sensor with a resolution of 0.01mm.

Figure 4 shows the diameter variation (whose nominal value is 1.75mm) in X and Y axis, from different filament brands (Formfutura, BQ, MakeMendel, Lanu).

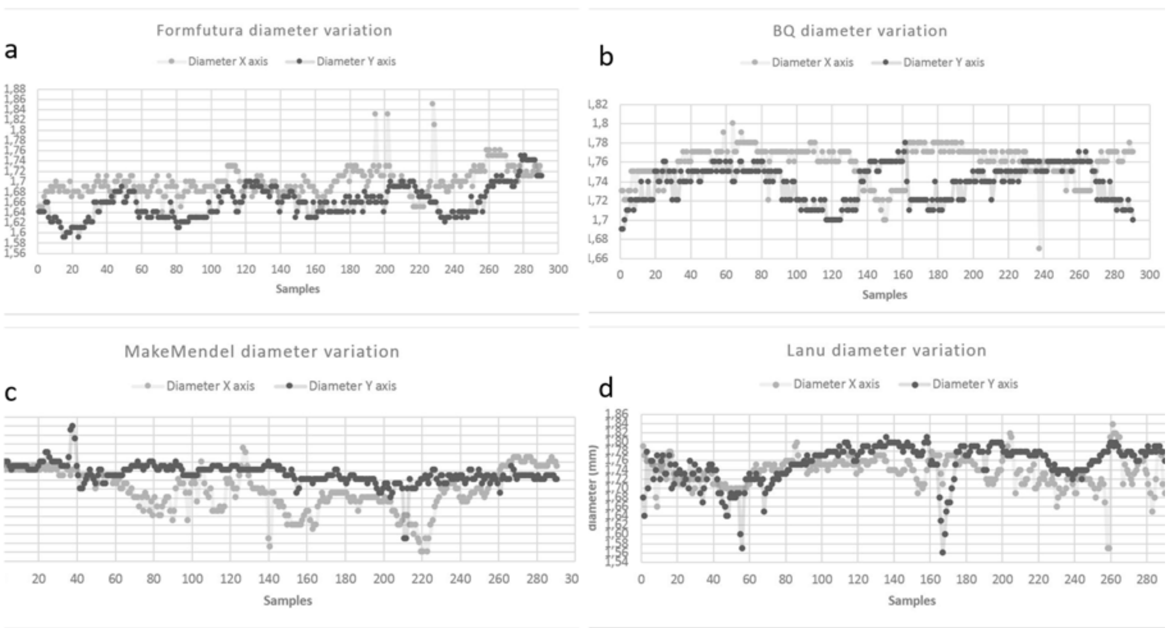

Figure 4. Diameter variation

By analyzing these samples (see Table 3), it is possible to see that the diameter varies from 1.59 mm to 1.85 mm, with an average of 1.68 mm in one case, and from 1.67mm to 1.8 mm, with an average of 1.75 mm in the other case. Booth filaments may obstruct the printer extruder.

Any of these failures makes that after leaving the printer in operation the piece that was being created is lost and it is necessary to start again. In addition, by continuing printing without really extruded plastic, the machine consumes energy and produces an unnecessary wastage. Due to this reason, the operator must be aware of the machine as long as it is operating, ensuring that the plastic flows without problem, which is especially difficult when the piece takes several hours to be produced.

Table 3. Maximum, minimum and mean of filaments

Brand	Maximum (mm)	minimum (mm)	mean (mm)
Formfutura	1,85	1,59	1,68
BQ	1,8	1,67	1,75
Lanu	1,84	1,56	1,75
MakeMendel	1,86	1,58	1,74

4.2 Evaluation of the implemented system

The installed system does not affect the print quality of the machine. It has been found that the time set for detecting advancing filament problems detects an error in time without producing false positives. In Table 4, the error is displayed on the printer.

Table 4. Error menu

Filament error. Push the button to change the filament.
Extract the filament when the motor stopes.
Insert the new filament and push the button.
When you see come out the filament, press the button to continue printing

In Figure 5 it is shown an object produced by a 3D printer where two filament feed errors were forced.

Figure 5. Model produced after two filament advance problems

5. Conclusions

The installed system achieves perfectly detect the advance of the filament without affecting the normal operation of the machine. The final frequency to check the advancing filament (every 5s) allows to detect any problem with it, and there are not errors that can appear if the sensor is checked with a higher frequency. While it is true that although had been raised as a possible option to detect the speed, with the sampling frequency set, it is not possible to calculate it, but meets the initial objectives of troubleshooting in advancing filament.

This has made possible the use of the printer with remains coil filament, which had not been used before because they were not sufficient to complete an impression. With this system, when the filament finishes, the printer enters into a standby state waiting for the user to introduce a new filament.

Therefore, the primary objective of the system is achieved, avoiding loss of material, energy and mechanical wear, keeping the premise of making a low-cost product that does not significantly increase the cost of the machine.

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