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Optical recognition of error states to secure quality in fused deposition modeling 3D printing

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Abstract: In common Fused Deposition Modeling (FDM) 3D printers there is no feedback loop to check whether the model is printed correctly. Due to extensive printing times, printers often run unsupervised. Most FDM 3D printers work with stepper motors, which only know the position of the print head relative to a home position. Missed steps or a detached print cannot be detected. To minimize failing prints, resulting hazards, and to improve printing quality, this work proposes to check the model continuously during the printing process with a camera and alert the user, if necessary. The results show that a detached print or a jammed nozzle can be detected

I. Introduction

Most 3D printing methods process a model by slicing it into thin layers, ranging from 0.05 to 0.3mm [1]. These layers are then printed one after another. This is also true for FDM 3D printers [2]. If necessary, the slicer adds support material or a print-bed raft and determines the number of perimeters and infill of a print among other parameters. The output is in 'gcode' format which is specific to the machine. It essentially tells the printer firmware where to move with a specific speed as well as when and how much material should be extruded. Before each print, the print head moves to a specific home position. All movements occur relative to this position. The machine translates the 'gcode' into stepper motor movements for each axis and for the extruder. Due to the motor movement, the machine moves according to 'gcode' paths of the model and positions the filament at the specified points and lines. Typically the filament of 3d printers using FDM technology is a thermoplastic material like PLA, ABS or PETG. Usually, each sliced layer is printed separately on top of each other, building up the model from the print bed.

I.I. Common problems of 3D printers

Due to large print sizes and the ambition of accurate prints, thin layers and the limited speed of filament melting due to its thermal conductivity, 3D prints often take many hours [3]. Therefore, these processes mainly run unsupervised. This can result in challenging situations (table 1). For example, plastic FDM 3D printers have a hot nozzle (180°C to 280°C)[3] and no way of telling whether or not they are still printing correctly or - in extreme cases - setting something on fire. Such an extreme case might occur if the filament is no longer extruded and applied to the print, but is staying stuck on and inside the nozzle accumulating and heating itself up over a long period. Apart from quality degraded prints and therefore waste of plastic due to the lack of monitoring, thermoplastic fumes and particulate matter occurring during thermal extrusion of the plastics are unhealthy. In the study of Zhang et al, it was shown that a wide variety of these particles, which are potentially toxic, are produced during the whole printing time at a high concentration [4]. They call for a laser printer alike particle emission classification. This shows that these particles are not to be underestimated. Therefore, it is not advisable to spend too much time next to, or even in the same room as a FDM 3D printer to monitor the system.

Table 1: Common printing errors and results on prints

Malfunction	**Consequence**	**Print result**
Stepper motor step skipped/ print head offset	Misalignment in x-y-direction or z-axis.	Consecutive layers might not stick. Could result in agglomeration on nozzle or unstable print
Print detached from print bed	previous layers lost, printing in air	Most likely agglomeration on nozzle/ random filament extrusion
Nozzle jammed or filament stuck/empty	No material can exit the nozzle	Filament heats up and burns in nozzle
Print head moves too fast	Curvy instead of exact geometry	Print may not be as precise as modeled
Frame oscillates/ Person bumps into printer frame	Print head oscillates	Printed lines are not straight

II. Material and methods

As a system can only be controlled if it is measurable, the malfunctions listed in table 1 need to be detected. For this purpose, two different methods were evaluated:
A calibrated webcam (640x480px) is mounted to the frame of the printer. The calibration is done intrinsically and extrinsically according to Z. Zhang[5] in OpenCV to account for distortions of imprecise optics, of camera assembly or of a skewed perspective. The camera is angled toward the print bed. This way, the emerging print is completely visible to the camera. Before the print starts the camera takes one image of the print bed without the printed object as background. After a layer is printed, the print head is driven to a pause position outside of the visible range of the camera and a frame is recorded. The 'gcode' for the printer is reconverted into a 3D model and rendered on to the calibrated webcam image. To measure

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the severity of the malfunction a similarity measure is calculated for each layer by following the image processing pipeline in figure 1. Background and webcam frame are subtracted from each other, the resulting image is filtered with the canny edge filter and dilated. The same preprocessing is done for the virtual webcam image of the render. The results are again subtracted from each other and the result is eroded to reverse the dilation. This erosion and dilation adds reliability against noise. Finally the white pixels in this binary similarity image are counted. The raw render frame is also filtered by the same canny edge filter and its white pixels are counted. The resulting two values are divided and scaled according to formula 1. The higher the value, the less accurate is the print compared to the model. Pixels in the final frame indicate where something has changed on the print bed or on the print in relation to the model. This process is repeated after each layer is completed.

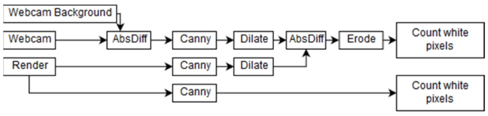

Figure. 1: Image processing pipeline of camera and render

$$\frac{\#\ \mathit{white\ Similarity\ Print\ Frame\ pixels}}{\#\ \mathit{white\ Render\ Frame\ pixels}} * 100 \qquad (1)$$

In another 2D attempt, the same camera is mounted to the moving print head, next to the nozzle. It is angled at the nozzle in such a way, that mainly the currently printed section is visible. The image is rectified by extrinsic calibration, to display angles correctly even though the image was taken at a skewed angle. Therefore, distortion effects are eliminated. The position of the print head is saved alongside each frame. After each layer, all images of the same layer are merged together according to the print head's position. Finally, the canny edge filtered layer image is compared to the 'gcode' generated layer image.

III. Results and discussion

For the camera on the print head, the alignment between the print head position and the frame with a slow shutter speed and rolling shutter prevented this approach from being successful. However, the camera attached to the printer frame was able to detect various rough print errors as seen in the table 2 below.

Table 2: Common printing errors and detectability by method

Malfunction	**Frame camera**	**Head camera**
Stepper motor step skipped	Probably detectable at higher resolution	Not detectable
Print detached from print bed	Detectable	Not detectable
Nozzle jammed or filament stuck	Detectable but only after a couple of layers	Not detectable
Print head too fast	Not detectable	Not detectable
Frame oscillates	Not detectable	Not detectable

For each layer the values of three different prints of the same model were plotted against each other which is shown in figure 2. The good print is indicated by the grey curve running approximately parallel to the x-axis as errors do not build up. The curve with the steepest slope indicates the worst case of a failed print: the print detached from the print bed at layer 12, and the print was aborted at layer 34. The dashed curve shows a print where the nozzle clogged at layer 39, leading to degrading print quality for each layer after layer 39. Observations show that a good print stays below a certain threshold and more or less follows a straight line, whereas failing prints tend have a rising slope, and deviate a lot. These tendencies were observed on a number of different models and print settings on the same printer. Fluctuations on a good print are mostly due to the background extraction not working properly due to lighting changes in the room.

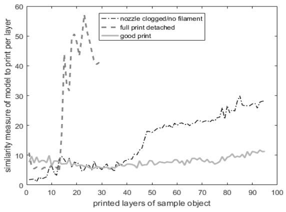

Figure 2: Similarity measure between print and printed model of three prints of the same model. It shows a good print, a print detaching from print bed and failing at layer 12 (print aborted at layer 34) and a print with a clogged nozzle at layer 39

IV. Conclusions and future work

Checking the print with frame mounted camera is a good addition for 3D printers running in many workplaces and homes. Such a simple and cheap camera is often already installed or can be added easily to detect errors effectively which are hard to measure otherwise. The results could probably be improved with a higher resolution camera or multiple cameras from different angles. However, this would also increase the processing power required as the 3D rendering resolution would also have to be increased. The camera on the print head could be successful if a small, lightweight and cheap high-speed camera with a global shutter was available and attached. This is currently not expected to happen. The rolling shutter could potentially be corrected through a software approach, because the speed of the print head is known. However, common 30fps cameras are not fast enough for reasonable print speeds.

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