CARINTHIA UNIVERSITY OF APPLIED SCIENCES

SYSTEMS DESIGN MASTER'S

DATA ACQUISITION AND TRANSMISSION

FEASIBILITY REPORT

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Introduction

3D printers have taken over the world over the last decade and they have found many use cases in industry, as well as in homes. The convenience of producing parts with variety of materials at the comfort of homes gathered attention of many hobbyists and makers. In industry, the increasing market demands and production speed of 3D printers have made them suitable for rapid-prototyping; saving immense amount of time and money. Civil engineers and architects also found use cases for 3D printers. For example, Mayorship of Istanbul has built its own 3D printed local service buildings within a week and with a fraction of cost and build complexity.

Most 3D printers are based on the technique called *Fused Deposition Modelling.* Detailed definition will come on the next subsection but for now it suffices to know that this technique is based on laying molten plastic on (initially) a flat surface, then on the part's previously laid layers. Since melting is involved in FDM, high temperatures are of concern. Also, as temperature stability affects part quality, it is of high importance that the temperature is well-monitored. For this purpose, positive temperature coefficient thermistors are employed.

This feasibility study will focus on FDM printers in which plastic filaments are employed as raw materials. The circuitry and calculations will be based on the work of the *Sensor Models* class of Mr Bernd Philipitsch and an open-source Makerbase Gen v1.4 board. Further calculations and values will be fetched from respective datasheets of components.

Definitions of Components

Following are the definitions of all the terms that are related to this study.

FDM Technique: *Fused Deposition Modeling* technique employs disposing molten plastic on top of newly-frozen-plastic to fuse them together. Combined with 3 or more axial movement, this technique can fabricate engineering parts, ornaments, or figures out of polymer materials.

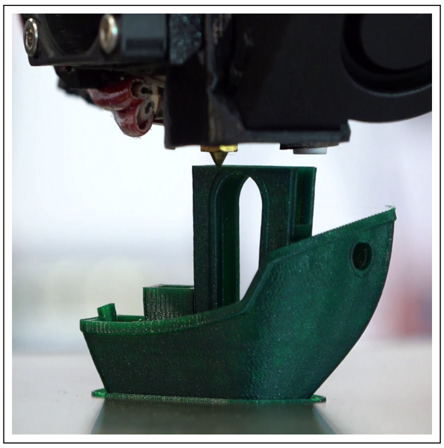

Figure 1: A close up of an FDM 3D Printer [1]

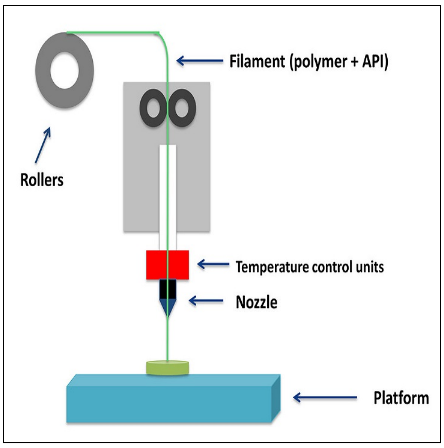

Figure 2: Overview of FDM technique [2]

PTC Thermistor: A special kind of resistor whose resistance value changes depending on its temperature. PTC stands for *positive temperature coefficient*, which indicates that the resistance of thermistor is proportional to its temperature. Such sensors are also called *RTD*, which stands for *Resistace Temperature Detectors.*

Heater Block: The aluminum or steel body with a heater element where the plastic is molten and disposed.

Figure 3: A PTC1000 sensor embedded in an aluminum skin [3]

Figure 4: An aluminum heater block [4]

Nozzle: It is a subcomponent of the hotend, through which the molten plastic meets its final destination. It can be made of brass, stainless steel, or titanium. Its orifice

Hotend: This is the roof term for assembled heater block, nozzle, and temperature sensor, along with other components which are not of importance for this study.

Figure 5: A stainless steel nozzle [5]

Figure 6: A partly assembled hotend [6]

Need For Temperature Sensor

Hotend temperature must be kept stable as fluctuations in hotend temperature would cause quality issues on the product, e.g. uneven surface finish and/or material deposition, or nozzle clog. Therefore, the frequency at which the temperature is measured plays an important role. Also, since the sensor is placed at the carriage, its weight plays an important role in position control. However, a PTC thermistor is never of high mass, therefore this study will assume that the mass of the carriage will remain relatively same.

Requirements

	Physical Requirements	Elctrical Requirements
	a	b
1	Size: Max 3x3x3 mm	Accuracy: $\pm$ 1 °C
2	Weight $<$ 2 grams	Connection Architecture: Voltage Divider
3	Measurement range: 20 - 270 °C	Power consumption $<$ 2 mW
4		ADC: 10 bits resolution, 0 - 5V range, rounding-based

Financial requirement: Project budget is 10$.

Component Selection

- MCU: Atmega328p [8] $\rightarrow$ Price: 1.57€ $\approx$ 1.76 $
- Sensor: TE connectivity PT1000 [9], Price: 3.41 $

The cost of the project, with only the two components in mind, is 5.17 $ at the time of writing this report (July 16, 2023). If the USD does not plummet within the upcoming week, **financial requirement will be satified**.

PTC1000 Sensor Characteristic

PTC1000 is a ubiquitous sensor with a *fairly* linear behavior across a wide range of temperature. The number *1000* in its name denotes that the resistance of the sensor at 0 °C is 1000 Ω. In the lecture *Sensor Models*, the sensor was scrutinized with the help of Matlab and its characteristics were obtained.

Calculation of resistance as a function of temperature is defined in international standard **DIN EC 60751** and is as follows [9] [10]:

$$R(T) = R_0.(1 + a.T + b.T^2) \tag{1}$$

where the coefficients are as follows:

$$a = 3.9083.10^{-3} \tag{2}$$
$$b = -5.775.10^{-7} \tag{3}$$
$$c = -4.183.10^{-12} \tag{4}$$
$$R_0 = 1000 \tag{5}$$

Then, the characteristic graph can be easily obtained with Matlab:

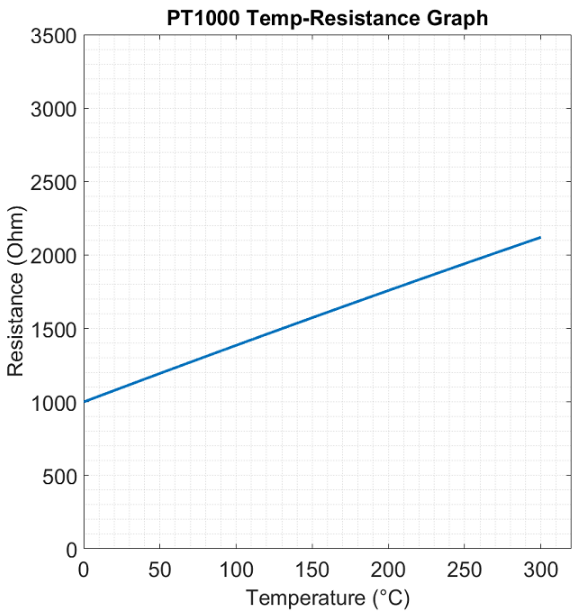

Figure 7: Chatacteristic graph of the PT1000 sensor

As it is evident from the graph, the temperature domain response is *fairly* linear, which means that there is no visible nonlinearity, and that data extraction from the sensor will be a rather light work for the MCU. This aspect will save substantial amount of computational resources.

Further, it is possible to extract a scalar for the sensor which rates the increase in resistance to increase in temperature or vice versa. The tangent of the line will yield in this value of interest. Before this calculation, the resistance value for 300 °C has to be determined, which is:

$$R(300) = R_0.(1 + a.300 + b.300^2) \tag{6}$$

$$R(300) = 2120.51\Omega \tag{7}$$

Then employ this value:

$$\alpha = \frac{2120.51 - 1000}{300 - 0} \frac{\Omega}{°C} = 3.735 \frac{\Omega}{°C} \tag{8}$$

So, for every 1 °C increase on the sensor, its resistance will rise by 3.735 Ω. Likewise, the scalar for obtaining temperature out of resistance value can be calculated as follows:

$$\beta = \frac{1}{\alpha} \frac{°C}{\Omega} = 0.2677 \frac{°C}{\Omega} \tag{9}$$

This means that every 1 Ω increase in sensor resistance is due to 0.2677 °C increase in its temperature.

One thing to note for the PT sensors is that they also function below 0 °C. However, it is of no use for the application, therefore it will be skipped [9].

Now that we know how the sensor behaves, how do we obtain data from it? There are a few options to connect a thermistor to an MCU. One of which is a Wheatstone Bridge, which Mr Philipitsch covered in Sensor Models lecture; the other is a simple voltage divider, which is what's employed on many boards in the market due to its simplicity and cost-effectiveness [7]. As required, voltage divider architecture will be analyzed.

Voltage Divider

A voltage divider can be implemented as follows:

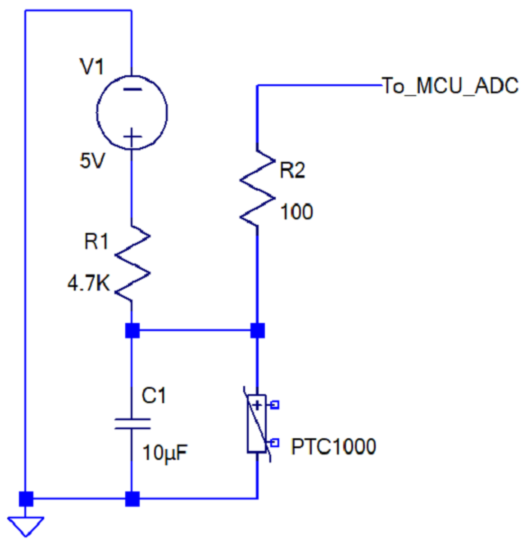

Figure 8: PTC1000 connected through a voltage divider[7]

The above circuit is an example from a board available on the market. [7] The voltage source is chosen depending on the logic level of the MCU, which was 5V. The capacitor *C1* is placed for filtering purposes.

R1 is the first step in the divider and chosen according to the ADC specifications and market availablity. It is chosen as $4.7K\Omega$ since this value is the sweet-spot between linearity and output voltage range. What this means is that if a higher resistance value was picked, the sensor response would be more linear at the expense of output range, or vice versa. The ADC on the MCU is 10 bit and it can detect between 0 - 5V. This means that the ADC can detect every 0.0049 volts of change (so-called *LSB* value of the ADC). As we are concerned about a 250 °C range, an output range of 1.225 V is the absolute minimum.

R2 is placed for protecting hardware against short-circuit in case of component failure.

Physical and Financial Requirements

The chosen sensor for measurement **satisfies all physical requirements 1a, 2a, and 3a.**

Electrical Requirements

Since how the sensor behaves is known, it is now time to calculate the voltage range for the thermistor. The voltage on the sensor can be calculated as follows:

$$V_{thermistor} = 5V * \frac{R_{thermistor}}{R1 + R_{thermistor}} \tag{10}$$

Since $R_{thermistor}$ varies between $1000 - 2120.51\Omega$, we can calculate the voltage across it with respect to its resistance. Further, we can extend this calculation to show the relation between temperature and voltage across the sensor.

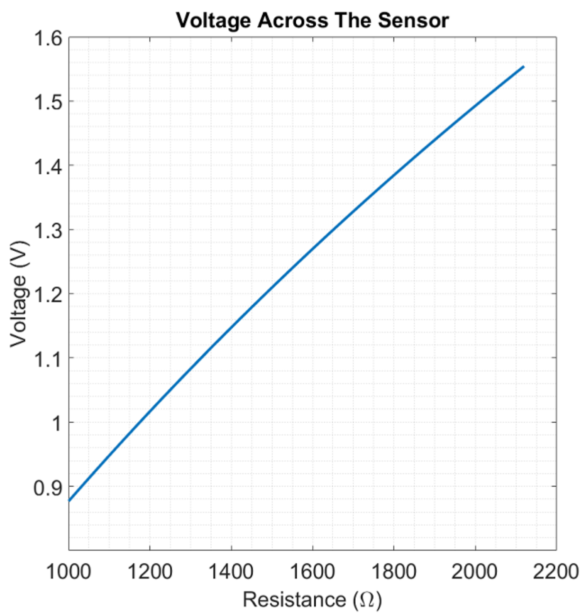

Figure 9: Voltage - Resistance graph

The lowest voltage across the sensor is:

$$5 * \frac{1000}{1000 + 4700} = 0.8772V \tag{11}$$

and the highest voltage across the sensor is:

$$5 * \frac{2120.51}{2120.51 + 4700} = 1.5545V \tag{12}$$

Both of which are within ADC limits, **hence Requirement 4b is satisfied.** However, the required resolution of detection of 1 °C **(Requirement 1b) is not satisfied** since it necessitates a larger voltage range across the sensor:

$$270 - 20 = 250°C \text{ (or steps)} \tag{13}$$

$$1.5545 - 0.8772\,V = 0.6773V \tag{14}$$

$$\frac{5}{10^{10}}\,\frac{V}{step} = 0.0049\,\frac{V}{step} \tag{15}$$

$$\frac{0.6773}{0.0049} \approx 138 \text{ steps} \tag{16}$$

The requirement was that the setup is able to detect 250 temperature steps; however, the it is only possible to detect 138 steps, **hence Requirement 4 is not satisfied.** Increasing the ADC resolution to 11 bits would do away with this shortcoming, as LSB would drop 1 fold (to 0.00245), therefore the number of detectable steps would increase 1 fold (to 276 steps). One thing to note is that the ADC will register every 1.8116 °C change on sensor. This may mean hardship for temperature controller as hotend temperature needs to be kept stable and a swing of temperature with 1.8116 °C in amplitude could render prints useless.

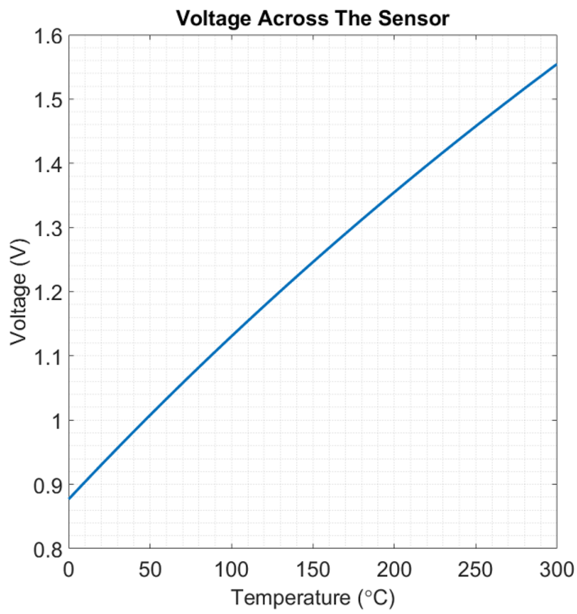

Figure 10: Voltage - Temperature graph

From this point on, it is necessary to figure out a way to obtain temperature value. Following equation is used for determining the temperature - voltage relation. This formula can also be used on software side as well to detect temperature:

$$\text{Temperature} = \frac{V * 4700}{5 - V} \tag{17}$$

What makes this equation possible is the linear relation between temeperature and resistance, which was demostrated in previous section. Now that temperature is written as a function of voltage, next thing to do is to convert voltages into digital values, that is, integers written in binary.

It is known that the ADC turns voltage values between 0-5V into binary integers at certain LSB intervals. 0V corresponds to 0, 1*LSB V equals to 1, 2*LSB V equals to 2, and so forth. So with (17) in mind, it is possible to write the following formula:

$$\text{ADC Output} = \frac{V_{thermistor}}{LSB} \rightarrow \text{Temperature} = \frac{\text{ADC Output} * \text{LSB} * 4700}{5 - \text{ADC Output} * \text{LSB}} \tag{18}$$

Based on ADC architecture, either *rounding-based* or *truncation-based*, equation (16) is either rounded or truncated. Since requirement 6 states that the ADC is rounding-based, (16) will be rounded up if decimal value is above .5, or floored if the decimal value is below or equal to .5.

The lowest voltage across the sensor was found to be 0.8722V, which equals to:

$$\frac{0.8722}{0.0049} = 178 \tag{19}$$

Then, the corresponding binary integer value for the highest voltage is:

$$\frac{0.8722}{0.0049} = \lceil 317.2449 \rceil = 317 \tag{20}$$

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