Sensors on 3D Printers for Cloud Printing Service

F. Baumann¹,*, J. Eichhoff¹, D. Roller¹ and M. Schön²

¹IRIS, University of Stuttgart, Stuttgart, BW, 70569, Germany
²IFW, University of Stuttgart, Holzgartenstraße 17, Stuttgart, BW, 70174, Germany

*Corresponding author

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Abstract. In this paper the design and implementation of a sensor array suitable for 3D printers is presented. The sensor array includes sensors for motion/vibration, temperature, orientation and hygrometry. The sensor array is designed as an easily deployable, wireless sensor client-server system. The sensor data is used in a cloud based printing service as remote supervision capability. Users of the service are enabled to monitor the printing process and store associated sensor data for future use. Aggregated sensor data and print related data enable research on influencing ambient factors and quality control of the printing process. In future revisions this sensor system is intended as part of a closed-loop control system for 3D printers. The sensor nodes are based on off the shelf components for easy assembly and cost-sensitive deployment. The wireless connectivity also enables the system to be incorporated in other machinery on movable parts, in our research setting this is a CNC milling machine. This research is aimed to smartify existing machinery within the paradigm of Industry 4.0. The sensor data from 3D printers provided enables better control and supervision of the printing process.

Introduction

Printing or Additive Manufacturing (AM) is the process of creating physical objects from digital models by layer-wise material deposition or hardening [1]. Technologies for AM include Fused Deposition Modelling (FDM, trademark by Stratasys Inc., also Fused Filament Fabrication FFF), Laser Sintering (LS) and others. We focus our research on FFF where thermoplastics are extruded from a print head along a pre-programmed toolpath.

During the printing process, errors may occur that lead to failed prints resulting in lost time and wasted material [2, 3]. Consumer grade 3D printers do not detect print failures as they are designed mostly without feedback mechanisms. Missing material, detachment of the print object or deviations from the model [4] is not detected by the printer. Missing material flow is only detected by some printer hardware, e.g. MakerBot's SmartExtruder and SmartExtruder+. Print failures can be detected visually by inspection or remote supervision using video cameras [5], acoustic emissions [6] or by utilizing sensor data [7]. Providing additional modular sensor nodes to the printer can help in detecting deviations from the intended print early [8].

With this research we propose a low cost modular sensor array that is added to a consumer grade 3D printer. As this type of machine is not regularly equipped with a climate control chamber for prints the environment factors like temperature and humidity are often not recorded for further inquiry into errors, failures and normal prints. Additionally we intend this sensor array to be evolved into a system capable of actively controlling the print as a closed-loop system. For this work we have set the following two research questions: 1) How can sensor arrays be designed cheaply and in a modular manner for the use in a FFF printer scenario so that the sensor data is of high quality for inquiries on the printing process and its failures? 2) How can the sensor data be incorporated into the 3D printing service and provide suitable information to the user?

For the first question we set the requirements of the system to be: 1) Cost-sensitive as multiple sensor nodes per printing resource are to be deployed, 2) Modular as various sensors are to be
deployed depending on the research requirements. This has to be reflected in soft- and hardware, 3) Small as the sensor nodes are to be deployed on the printing head that has high geometric restrictions, 4) Wireless as the sensor nodes are also intended for machines with rotary parts.

For the implementation of our prototype we have equipped a MakerBot Replicator2X printer with sensors. The remainder of this paper is structured as follows: After this section we briefly discuss related research on quality assessment and process control of FFF printing. In section [3. Hardware] we describe available hardware on which the prototype implementation is based on. Following this, we describe the implemented architecture of the sensor system and the printing service. In section [5. Preliminary Results] we discuss preliminary results and problems encountered with this system. Section [6. Discussion and Conclusion] concludes this paper and section [7. Outlook] provides implications on future research.

Related Work

This section reviews contemporary work that is related to in-situ quality assessment and failure detection of the FFF printing process. With automatic quality assessment the user is supported in the supervision of the print. In recent work of [7] a similar sensor system for the online analysis of printing quality in an experiment is proposed. In this work a nonparametric Bayesian Dirichlet Process (DP) mixture model and Dempster-Shafer Evidence Theory (ET) is applied for a heterogeneous set of sensors attached to a 3D printer. The authors detect printing failures in real time with an accuracy rate of 97%. As part of the printing service user interface (UI), the authors Ludwig and Pipek [8] describe Arduino based sensors integrated into a UI. These sensors are part of the user's dashboard for online print supervision. The focus of their work is on the concept of appropriation of 3D printing. In Lott et al. [9] the authors describe an optical supervision system for another AM technology. This system provides necessary information for a closed-loop process control system. Similar work is described by Craeghs et al. [10] on Selective Laser Melting (SLM) for the purpose of process monitoring. For EBM manufacturing, Dinwiddie et al. [11] propose an optical system for layer-wise process monitoring with the aim of process control. Most of the recent research is in the state of working prototypes without actively controlled processes and specific for a class of AM machinery. Research on the integration of sensor data into user interfaces (UI) of printing services is only described by Ludwig and Pipek [8].

Hardware

A precondition for the proposed sensor nodes is mountability as a supplement to existing 3D printers. This limits the package size for internal nodes due to geometrical restrictions, especially for the sensors that are located at the printing head and the printing bed. The size limitations are 9x25x40 mm for sensor nodes for the printing head in this case. Externally mounted sensors or sensors that are not mounted on rotary parts can be powered by cables. Attachment on rotary parts is intended for the future use case in milling machines. The attachment of the sensor nodes on the printer is restricted by the capability of the sensor to detect valid sensory inputs. Placement of sensors is required to be rigid and stable. Sensor node attachment must also be non-permanent as the system is designed for flexibility.

Besides the restrictions laid out above, another goal is to incorporate open soft- and hardware in order to ensure easy future modifications and maintenance. The system design is modular and flexible thus requiring a carrier platform that enables flexibility and wireless connectivity.

Various platforms exist that are suitable as a base for the sensor node. These platforms can be divided into a) small computers and b) micro controllers with a further divide in bare micro controllers and micro controllers with prototyping infrastructure. In an initial step we have compared the limitations and benefits of the following platforms, data is available externally: a) Raspberry Pi, b) BeagleBone Black, c) Arduino (Uno), d) Arduino (Nano), e) RFDuino, f) JeeNode, g) ESP8266.
We chose the ESP8266-12E platform as it fits our requirements and constraints best. The system is available in large quantities from a wide range of vendors for a very low price thus enabling a high number of sensor nodes per machine. Additionally, this platform is supported by a large group of developers and users ensuring adequate support.

Available sensors can be categorised as follows:

- Sensors for Environment/Ambient Factors:
  - Temperature
  - Pressure
  - Volatile Organic Compounds (VOC)
  - Magnetic Field Strength and Orientation
  - Hygrometry
  - Sound Level/Loudness
  - Brightness
  - Gas

- Power Related Factors:
  - Power
  - Voltage
  - Current

- Resistance (of parts, e.g. printing bed, extrudate)

- Distance/Range (of moveable parts within the printer)

- Acceleration

-Object deformation (e.g. bending or stretching)

Due to restrictions in size, the tables and images can be found at http://www.iris-uni-stuttgart.de/amsme-paper.html. From tab.2 we select one of the multi sensors first and combine it with a sensor board that is of further interest. A combination of GY-80 and GY-87 with other multi sensor PCBs is not possible. The combination of GY-81 and GY-85 yields an overlap of the HMC5883L magnetic sensor as well as an overlap in the detection capability of acceleration data. In an initial testing phase we select the following sensors and sensor carriers. As sensor carriers we test a Arduino Mega2560, Teensy, Arduino Leonardo and ESP8266-12E as we relax the dimensional requirements for sensors mounted on the outside of the printer to arbitrary values. As sensors we test GY-29, GY-45, GY-61, GY-80, GY-85, GY-88, GY-271, GY-521, KY-040 and GP2Y1010AU0F for suitability. For the initial selection of suitable sensors in the sensor nodes we compile tab. 2. In this first iteration various low cost sensors are examined and checked for fitness with our constraints and requirements. Integrated sensor boards are selected for easier assembly. Later iterations are to be made as custom printed circuit board (PCB) with sensor modules mounted directly.

**Power Calculation for Sensor Node**

Each sensor node is concepted as wireless and requires a portable power supply with a minimal footprint. The sensor nodes are powered with Lithium-Polymer (LiPo) battery packs that provide 400 mAh at 3.7 V at a weight of 9g and a form factor of 0.5x2.5x3.5 cm. A theoretical maximum run time for this setup is:

\[170 \text{ mA (TX in 802.11b) } + 10 \text{ mA Sensor } = 180 \text{ mA } \times 3.6 \text{ V } = 648 \text{ mW} \]

\[400 \text{ mA (in Battery) } \times 3.7 \text{ V } = 1480 \text{ mW} \]

\[1480 \text{ mW } / 648 \text{ mW } = 2.283 \text{ h run time} \]

Power measurements indicate that the real power consumption is lower than calculated thus enabling run times longer than two hours. With the current setup supervision and data acquisition of long lasting prints is not possible. Larger battery packs can be used to enhance sensor node run time but are restricted in placement. Added weight to the printing head changes the behaviour of the printer as the motors are designed for a specific weight of the print head.

**Architecture**

Based on the initial test setup we propose a system design with multiple modular sensor nodes attached to a dispatcher system via WiFi (IEEE 802.11b). Within this system, the dispatcher is responsible for acquiring data over the air interface sent from the sensor nodes. The expected sensor data acquisition rate of 200Hz results in a 13.48 KiB/s data transfer rate. On average the sensor nodes are equipped with two sensor PCBs with each PCB containing one to four sensors. Each sensor provides 10 to 14 bit data resulting in a maximum of 112 Bit data per measurement, with an additional overhead of 3 bit sensor identifier, 4 bit sensor node identifier, and 12 bit timing information.
Hence, total data per measurement is estimated at a maximum of 131 bit per measurement at a rate of 200Hz resulting in 26200 bits per second or 3.198 KiB/s. Utilizing raw TCP/IP over IEEE 802.11[12] adds 20 bytes (Layer 3) and 32 bytes (Layer 2). By sending every measurement on occurrence 69 bytes are sent each resulting in 13.48 KiB/s for each sensor node as a maximum. This is well below 11 Mbps (Megabit per second) or 1342.77 KiB/s. Alternatively sensor data can be cached on the sensor node. The ESP8266 provides 80 KiB of dynamic ram (DRAM) that can hold about 5850 sensor samples or 29.2 seconds of sensor data at an acquisition rate of 200Hz. By using local caching the capability of (near) real time data processing for active control is lost.

For the application of the sensor nodes we selected the highlighted positions in Figure 2 within and attached to the 3D printer. Position 1 on the print head is the most space sensitive placement but required to capture sensor data from the movement of the print head. Pos. 2 is between the underside of the printing bed and its carrier. This position is height restricted and a sensor node cannot be attached to the printing bed directly due to limitations of the sensors operational temperature range. The printing bed is heated to approximately 110°C. Pos. 3 is on the outside of the 3D printer and is intended to measure vibrations of the printer frame. Pos. 4 is on top of the printer and is intended as placement for the dust particle sensor to research particulate matter emitting from a 3D printer during printing. Pos. 5 is located at the backside of the 3D printer where the filament spools are. This location is intended to measure filament flow utilizing a rotary sensor.

The programming of the system is in C for the sensor nodes and Python for the dispatcher. The system is implemented in standalone mode where data is stored either on the dispatcher locally in a database or using a remote web service. The intended use case for these sensor nodes is within a remote printing service that provides 3D printing capabilities to users. Within this use case the sensor nodes are integral as they supervise the printing process and allow the printing service to control the process based on data provided. Furthermore, we enhance the sensor data by acquiring internal state data from the printer and correlate this to the sensor data.

The user interface of the printing service is programmed in Python using Flask. It features the following capabilities: a) Monitoring the print using a webcam, b) Charts for live and historical
sensor data, c) 3D representation of the print-head position, d) Control over the 3D printer utilizing USB serial connection and e) File management including object models and sensor data.

Sensor data is acquired by a component of the system using USB serial connections to the sensor nodes. A management component stores the sensor data persistently in a MySQL database. The users are enabled to interact with the printing process through the user interface component that instructs the management component. A connection component connects to the 3D printer and generates GCODE for interaction. The communication with the 3D printer uses an implementation of the S3G protocol specific to this machine.

**Preliminary Results**

With the initial design of the sensor nodes we have captured results from a test set with 5 different patterns in 2 variations for a total of 100 runs available. Further data from other objects printed yields a total of 159 test data sets. From the print runs there are 86 (54.08%) out of 159 with complete data, 70 (44.02%) with partial data and 3 (1.88%) with failed data acquisition. Data acquisition rates ranged from 131Hz to 391Hz with an average rate of 330Hz. Data acquisition rates depend in our case on the utilization of the system processing and storing the acquired sensor values.

For all sensors we see noisy data with the GY-61 (ADXL 335) sensor providing high frequency noise during data acquisition. The ADXL 345 sensor placed on the print-head (see Figure 2 Pos. 1) delivers high frequency noisy data for X and Y direction when printing. The ADXL 345 sensor data does not provide indication on the quality of the print head's movement.

For this work we have not implemented data filtering and smoothing as this leads to reduced data rates. From the datasets we can deduce printing times for different objects based on the sensor data for movement of the print head and a-priori knowledge of the print process. Knowledge necessary for deduction is movement of the print head during warm-up of the extruder and movement to parking position on completion. From the dust particle sensor no particulate emission during the printing process can be detected.

![Figure 3. Display of charting capability on historical sensor data.](image-url)

Figure 3 demonstrates the charting of historical sensor data during a print. The charting functionality is capable of displaying varying scaling for different sensor data. During our test series we encountered the following problems that we want to discuss: a) Availability of USB devices in Linux is erratic, b) Programmatic re-attachment for USB devices in Linux does not work as reliable as needed thus requiring manual intervention, c) Space requirement for test runs: Files are large for long prints which can lead to problems due to file system restriction. d) Noisy sensor data, e) Missing file format for storage of aggregated data, f) Detection of failed sensors is not implemented. Auto calibration is unavailable for some sensor types, g) How to detect start/stop of print reliably, h) State detection is possible for human experimenter.


Discussion and Conclusion

A system of low cost, modular and flexible sensor nodes for application on 3D printers is being developed. This sensor system is included in a 3D printing service to enable users to monitor the printing process. The sensor data is stored for failure analysis and identification of influencing factors. We discuss the architectural and design decisions for this system that can be used for research on additive manufacturing of FDM objects with consumer grade 3D printers.

Further uses include integration in 3D printing services for remote supervision. From remote supervision the next iteration aims for direct control of the 3D printer. The sensor nodes can enable users to gather sensorial data on the 3D printing process for a better understanding on the influencing ambient and machine-inherent factors during printing.

From the 159 test runs performed we are able to distinguish the machine state between printing and not-printing. We indicate that the goal is to expand the state detection to various error cases. Errors encountered during the design and implementation of the sensor nodes are discussed with possible solutions provided, but in this phase not all the problems are solved.

We acquire a large data set and keep collecting sensor data during further research on the 3D printer. This data becomes historical data providing insight on the performance of the 3D printer during its lifetime. For the second research question we state, that the sensor data must provide reliable and clear information on the status of printing. We aim to implement the necessary changes and improvements in later revisions for more reliable data.

Outlook

As a future work we suggest improvements on the design and integration of the sensor boards onto specialised PCBs. Further possible research is suggested for the object detection based on acquired sensor data. For the integration in a 3D printing service the data must be stored remotely, e.g., in a web service which adds latency thus reducing the capability to act as a real-time data provider for closed-loop control of the printing process. We suggest research on how sensor can be processed locally within such sensor nodes and be offloaded to remote services at the same time. With better platforms, higher computing power on ICs and smarter data processing this becomes possible. We recommend research on the usability of the sensor data provided and its usefulness for enhancing print quality. As an integrative file format for storing associated print data is missing we propose research into such a file format.

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References


