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Substrate Tubing Heater Suitable for Large Volume 3D Printing with Extrusion of Thermo-Reversible Hydrogels

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Abstract. The advancement of 3-dimensional printing technology over the past ten years has raised interest in and accessibility to these devices. Due to its consistent growth and demand, 3D printing is becoming a consumer-friendly, reasonably priced craft. Due to technological advancements, it is becoming increasingly integrated into broader fields of science and research, as well as the manufacturing sector. The need for customized solutions is constantly growing across several industries. The 3D extrusion of hydrogels is advancing in the field of biomaterials with a broad spectrum of biomedical applications. Hydrogel extrusion prints heads often use stepper motors or pneumatic pressure systems to push the substrate onto a surface. These techniques are well-suited for materials with high viscosity. While these systems are usually bound to the syringe volume, a refillable reservoir enables them to print above the syringe's limitations .

We developed a low-cost standalone heating system for flexible tubes to control the temperature, hence avoiding jellification and clogging of the tubing system leading to the nozzle of the print head. The system connects to an in-house made peristaltic pump, which forces the e.g. gelatin through the nozzle with low pulsation, enabling us to extrude multiple layers of precise tempered gelatin. The heating system is based on easily available materials and electronic components and does not require expensive tools.

Introduction

In the last ten years, the technology for three-dimensional (3D) printing has changed and developed significantly, greatly increasing its accessibility and range of applications. It 3D printing technology was first used for industrial prototyping purposes, it is now a more economical and consumer-friendly device used in almost all sectors including education, and research, and even consumer manufacturing [1, 2]. Nowadays, additive manufacturing is essential in many fields of and engineering and scientific disciplines. It is used in chemistry, biology, materials informatics, and even bioengineering for the manufacture of complex and precise structures to an unmatched degree of customizability and efficiency.

These technologies operate by depositing successive layers of material to generate intricate three-dimensional forms, facilitating not only the creation but also the redesign and repair of objects, often using biomaterials. Among the most used methods is fused filament fabrication (FFF), by which a thermoplastic filament is melted in a heated chamber and depositing it layer by layer. This approach supports the direct printing of certain biomaterials, including collagen- and agar-based gels, and even the integration of multiple material components within a single structure. Because different biomaterials often require distinct thermal conditions for optimal performance, an advanced temperature control system capable of independently regulating specific zones is essential.

Driven by surging demand for personalized, application-specific solutions, additive manufacturing has become a disciplinary cornerstone. Particularly dynamic is extrusion-based 3D printing of hydrogels—a category of hydrated polymer networks featuring adjustable mechanical and biological properties. This technology shows exceptional promise in biomedical engineering, with applications including tissue scaffolds, drug delivery platforms, and regenerative medicine[3, 4]. The biocompatibility of hydrogels, combined with their tuneable gelation characteristics, make them ideal bio-inks for cell-laden constructs and controlled-release systems.

Extrusion-based hydrogel printing systems are typically actuated via stepper motor-driven mechanisms or pneumatic pressure systems. Both are well-suited for dispensing high-viscosity materials under controlled flow conditions. Pneumatic systems allow smooth pressure modulation, while mechanical systems afford precise volumetric control [5]. However, these setups commonly rely on finite-volume syringes, which limits print duration and scale. Scientific advances have been published with a 50 mL syringe combined with a Bowden setup nozzle system [6]. Recent innovations have addressed these limitations by incorporating refillable or continuous-feed reservoirs. By decoupling the material supply from syringe constraints, these systems enable prolonged, uninterrupted extrusion processes facilitating the construction of larger and more complex hydrogel structures [7]. This innovation opens the door to printing more complex structures and larger tissue scaffolds that are otherwise unachievable within the constraints of traditional syringe-based systems.

Requirements

This project's main goal was to create a modular, reasonably priced temperature control system specifically designed for extrusion-based hydrogel 3D printing. To maintain material flow and avoid clogging from premature gelation within the substrate tubing, precise thermal regulation is crucial when working with thermally sensitive biomaterials like gelatine. As a result, the system was created to satisfy the following fundamental needs:

- *Thermal Precision:* Keep substrate temperatures just above the gelation point of the particular material (for example, gelatine, about 36 to 40 °C).
- *Compatibility and Modularity:* Function as a stand-alone device that doesn't require changes to the printer's core electronics to work with current direct ink writing extrusion setups.
- *Ease of Assembly:* To reduce production and maintenance costs, use widely accessible and reasonably priced components.
- *User Accessibility:* Include a simple user interface for setting and monitoring temperatures, without the need for specialized software or tools.
- *Expandability:* Allow for multiple heating zones to be controlled independently, offering flexibility for future developments or scaling.

The system operates independently from the printer's main electronics, powered by a dedicated 12 V DC power supply. An Arduino nano V3 microcontroller was chosen for its ability to handle multiple inputs/outputs and for its support within the open-source hardware ecosystem as well as price. A custom-designed circuit board facilitated clean integration of the sensors, heating elements, user interface, and power distribution.

To enable automated and responsive control of the heating process, a PID control loop was implemented. This algorithm continuously calculates the difference between a user-defined target temperature and real-time sensor feedback. It applies corrective adjustments using proportional, integral, and derivative terms to stabilize the system, minimizing overshoot and steady-state error. The flexibility and performance of the PID mechanism make it particularly well-suited for dynamic bioprinting environments.

Thermal Conditioning of Substrate Tubing

To meet the requirement of precise and localized thermal control, a specialized heating mechanism was developed for the substrate tubing and shown as schematic in Fig. 1. The goal was to ensure the material remained in a fluid state throughout its transport path to the printhead, particularly for materials like gelatine that begin to solidify even at moderately low temperatures.

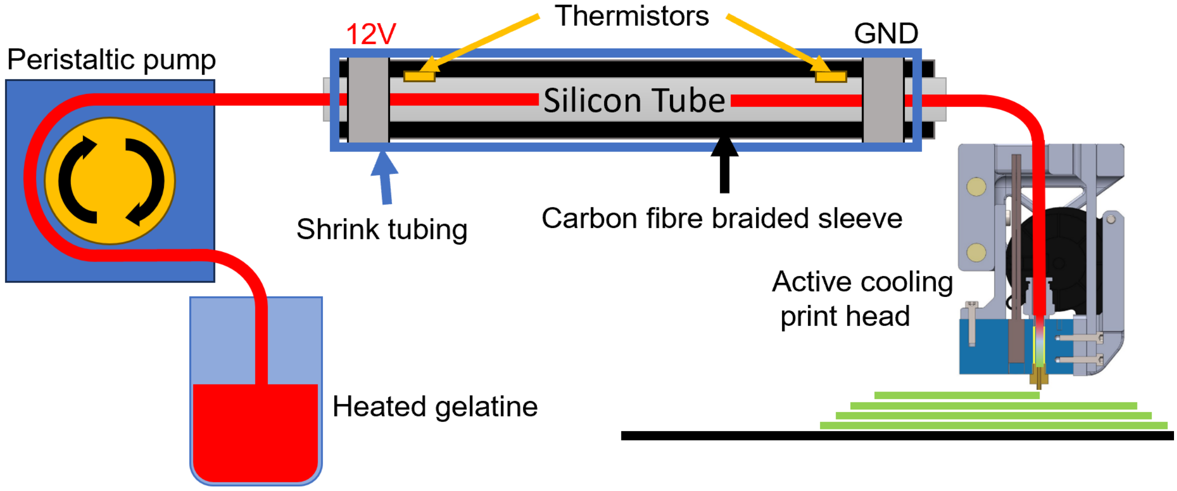

Fig. 1 Schematic overview of thermal gellable material extrusion process. Gelatine is headed to above the gelling temperature and pushed via peristaltic pump into the heated silicon tube which is connected to the actively cooled print head on the 3d printer to gel the substrate**.**

The thermal system employs a carbon fibre braided sleeve inserted into or wrapped around standard silicone tubing. This carbon fibre element serves as a resistive heating element, drawing power through the circuit board and regulated by the PID controller. Carbon fibre was selected due to its combination of properties of thermal conductivity, electrical resistivity, mechanical flexibility, and wear resistance enabling to withstand the continuous and repetitive movements of the printhead during the print process.

To provide precise and instantaneous temperature monitoring, two NTC 3950 100 kΩ thermistors were inserted at both tubing ends. These thermistors were selected due to their wide availability, ease of integration, and appropriate sensitivity. The Arduino Nano v3 processed their feedback and, using the output of the PID algorithm, modified the current supplied to the carbon fibre heating element.

The system's user interface was designed for simplicity and functionality. A standard LCD (128x64) display provided live temperature readings, while push-button inputs allowed users to set the desired temperature. The completed proof of concept prototype is displayed in Fig. 2. For further development a printed circuit board layout was designed (Fig.3), which needs to be manufactured in the future.

a b c

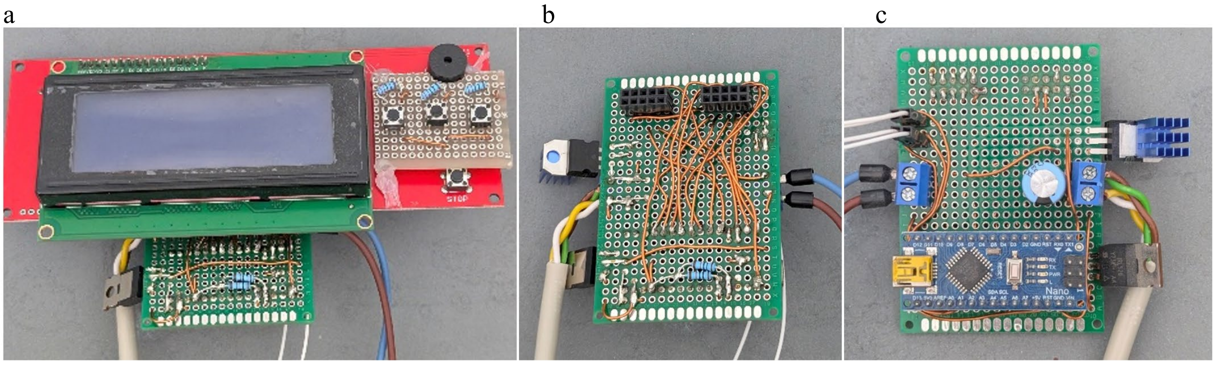

Fig. 2 Proof of concept prototype. (a) Control unit for tube heater with LCD display and control three buttons. (b) front side of circuit board without the LCD display and (c) backside of the circuit board with Arduino nano v3 terminal plug for power input, thermistors, power output for the carbon fibre braided sleeve.

This localised thermal regulation method guaranteed smooth, continuous material flow during printing and greatly decreased the chance of in-tube clogging due to substrate jellification. In addition to enabling the substrate to rapidly cool and solidify following extrusion, the ability to maintain a steady temperature slightly above the gelation threshold enhanced consistency and reproducibility in the creation of hydrogel-based structures.

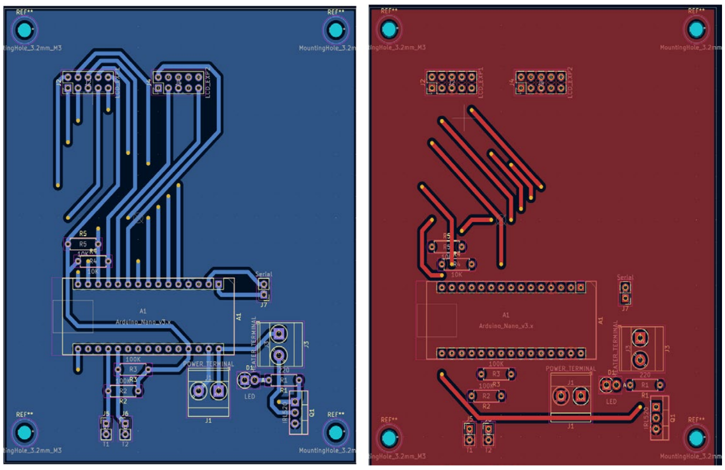

Fig. 3 Design for a double-sided PCB layout

Integration into 3D Biomaterial Printer

The developed substrate tube heater, an actively cooled extruder, a peristaltic pump, and a reservoir heater make up the extrusion system. A 10% gelatine solution was used to test the system. Using a heated plate and magnetic stir bar, the gelatine was heated above its gelling temperature, which is roughly 45 °C. To avoid clogging from contact with cooler tubing, the substrate tube heater was preheated for five minutes before extrusion.

Figure 4 displays the successful installation of the heating system in the 3D printer as well as the first gelatine printing outcomes. A side view of a printed gelatine cube with dimensions of 40 mm in width and 20 mm in height is shown in Fig. 4b. In order to assess layer definition and printing resolution, a more organic geometry with an indentation was also printed (Fig. 4c). The finished product was then compared to the green design model (Fig. 4d).

The structural integrity of freshly extruded gelatin presented difficulties during printing. Deformation and material leakage between layers could result from processing the material at an excessively high temperature, which would have prevented it from gelling in time for the subsequent layers to be deposited.

By increasing the fans on the cooling print head and fine-tuning the substrate temperature at the reservoir and heated tubing system, this effect could be avoided.

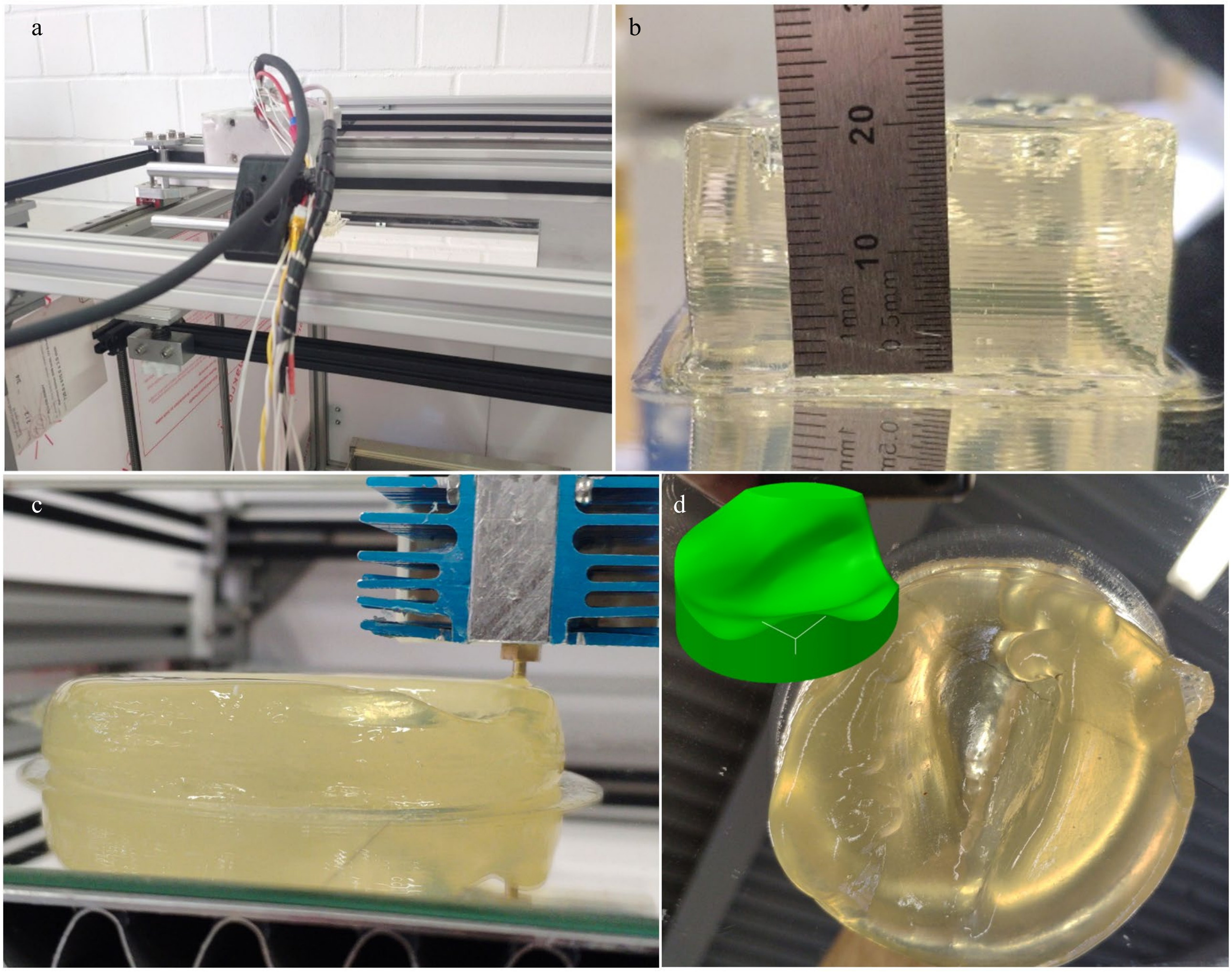

Fig. 4 Integration of the tube heater into the biomaterial printer and printing results with 10% gelatine. (a) View of the printer with the integrated tube heater system. (b) printed cube of 40x40x20 mm. (c) mid print of an organic indentation structure. (d) top view of the printed organic structure out of 10% gelatine and isometric view of the design file in green.

Summary

This paper provides a modular and affordable temperature control solution for the 3D printing of hydrogels using extrusion-based techniques. The system optimizes print material temperature control for the substrate by maintaining it a few degrees above the gelling point which promotes continuous flow of the material and enhances the print reliability. The system is easy to integrate into other setups because it is constructed from off the shelf parts and has a user-friendly interface and a PID control loop. The embedded thermistors and carbon fiber heating element thermistors provided temperature control and response needed along the substrate tubing.

Future research will focus on the effectiveness of the system by adding additional separately controlled temperature zones which will enable programmable thermal gradients along the tubing. We aim to add several sensors for better in-process control by monitoring the flow speed and fluid pressure which will enable the conditions to be monitored in real time for material transport. These improvements could enable the use of these systems to be used in closed-loop control which could increase the consistency and automation capabilities in the hydrogel bioprinting.

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