# PRODUCTION OF SHARKSKIN AT MULTIPLE REGIONS ACROSS AN EXTRUDER DIE

Commonwealth College Independent Honors Thesis

Mechanical Engineering Departmental Honors

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# ABSTRACT

Title: **Production of sharkskin at multiple regions across an extruder die**

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By carefully tuning thermal parameters near the exit plane of a die, it is possible to control the onset of sharkskin as a desired surface texture. It has been demonstrated that formation of sharkskin is possible at varying magnitudes in multiple locations across the outlet plane of an extruder die. In this paper, a method is outlined for fabricating a custom multi-zone extruder die designed for producing the desired multi zone surface features. Each zone of the extruder die can be utilized as an individual pixel capable of printing a range of texture. Subsequently an electronic control system was designed and implemented so that the limits of pixel resolution could be explored. As a proof of concept, characters were printed using initial open loop control schemes. Additionally, elements of a closed loop controller were designed and constructed for subsequent installation into the extruder apparatus. Furthermore, a rudimentary thermal simulation was developed as a diagnostic tool for predicting extruder performance.

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## Background

In certain operating regimes, it is possible to develop semi-periodic ridge structures while extruding various polymers through a die. Termed sharkskin in the literature, it is possible to develop these surface features to varying degrees depending on extruder operating conditions (see *Figure 1* for a cross sectional image of sharkskin).

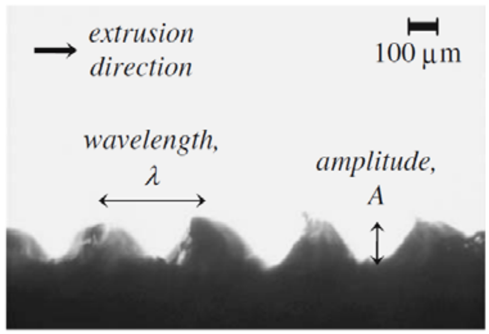



**Figure 1 –Cross Sectional Image of Sharkskin Texture. Wavelength and amplitude of surface texture are dependent on extruder operating parameters.**

The exact mechanics of the sharkskin instability are debated in the literature. It is clear however that sharkskin instability is correlated with the large surface stresses developed in the transition region between the no-slip boundary of the die wall, and the bulk velocity of the plug flow beyond the die (Arda and Mackley 2005). If the local shear rate is rapid enough, strain energy present at the stress singularity is dissipated in rapid deformation of polymer chains near the surface. The rapid loading and slipping encountered at the die exit plane results in periodic surface features of sharkskin (see ***Figure 2***).

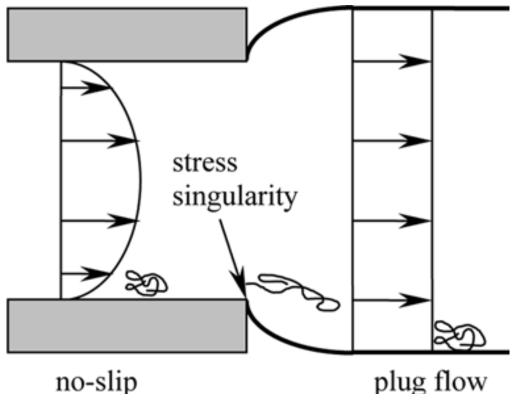



**Figure 2 -Schematic diagram of a capillary die exit geometry showing no-slip wall condition and plug flow in the extrudate, with inherent stress singularity. High local stresses at the die exit plane result in strong deformation of the polymer chains and large tensile stresses.**

## Previous Work

Work by Cogswell (1977) suggests that by altering die temperatures it is possible to control the development of sharkskin in polymer extrusions. Miller and Rothestein (2004) demonstrated that by controlling feed rate, bulk and die surface temperatures it is possible to develop the sharkskin instability to varying degrees with a circular die. By adjusting the operating parameters, it is possible to create surface features from mirror smooth to 0.5mm amplitude (as illustrated in Figure 3).

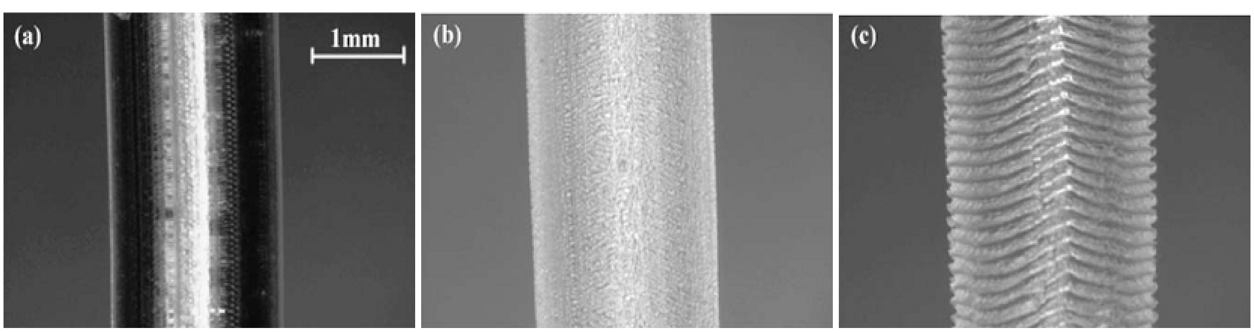



**Figure 3 -Series of photographs showing the transition from stable to sharkskin extrudate. From top to bottom: a smooth c_ ¼ 8 s1; b loss of gloss or onset of sharkskin c_ ¼ 16 s1; and c fully developed sharkskin c_ ¼ 50 s1: All photos are from the same experiment using Dow Affinity EG8100 LLDPE, extruded at Tbulk=140 C**

In subsequent work by Miller and Rothestein (2006), a method was proposed to produce a temperature gradient between opposite walls of a rectangular die (as illustrated in Figure 4). The resulting variation in surface features (correlating to corresponding die surface temperature) indicates that the surface instability is correlated with adjacent wall temperature, and is less affected by bulk polymer temperature. Due to the relatively low thermal conductivity of the polymer extrudate, it is possible to induce large local gradients without effecting operating conditions on adjacent die faces.

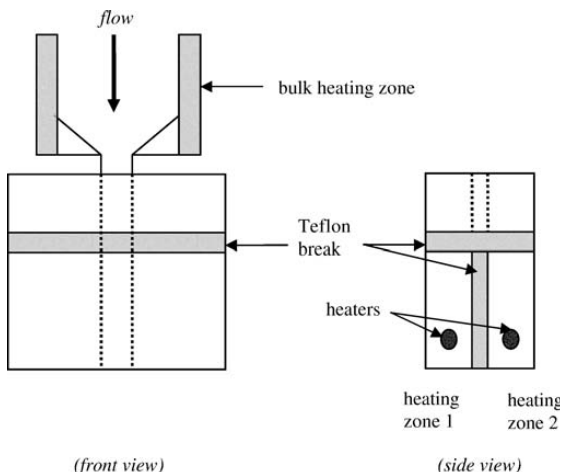



**Figure 4 -Schematic diagram of experimental extruder with rectangular die**

Similarly Rutgers et al. (2002) have demonstrated the production of a shark skin surface and a smooth surface on a film by controlling temperature gradients on adjacent die faces. Taking the work of Miller and Rothstein one step further, the local heater zones were treated as individual pixels capable of writing a range of texture from a glossy surface to fully developed sharkskin (see Figure 5). After implementing a multi channel temperature control scheme, the objective of this research is to demonstrate the feasibility of producing extruded surfaces with multiple zones of sharkskin across the same plane. As a demonstration of functionality, the multiple exit plane pixels will be utilized to produce extruded surfaces with legible characters produced by rapid control of induced temperature gradients.

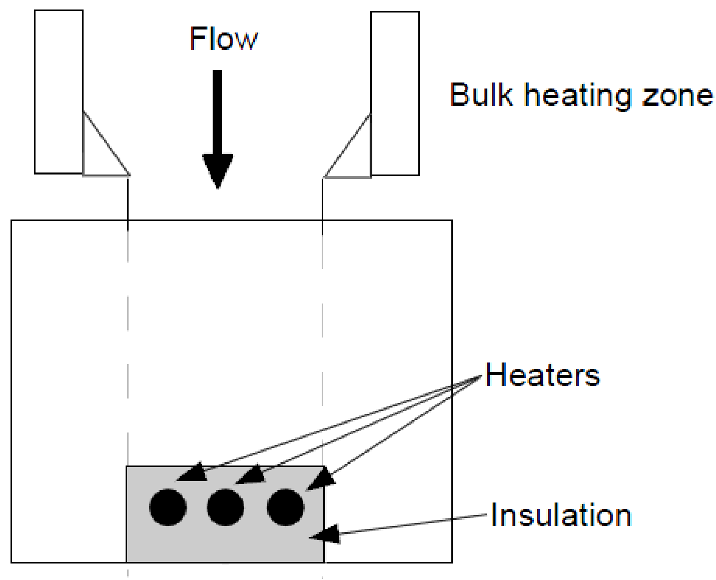



**Figure 5- Diagram of three thermal channel extruder die.**

**Development of Multi-Channel Extruder Die**

The amplitude of the induced sharkskin phenomenon is directly dependent on local temperature gradient and extrudate flow rate. From a rudimentary thermodynamic analysis it is evident that the magnitude of the supported temperature gradient across the die exit plane (see Figure 6) is dependent on the thermal resistance of the insulating materials used to physically and thermally separate the individual heater zones. In order to produce continuous temperature gradients, the die must be capable of removing heat from some zones while adding heat to others. Naturally, maintaining a larger temperature gradient requires larger heat flux at heated and cooled die regions. As expected, better performance is achieved by carefully selecting insulation materials, and reducing the thermal time constant associated with each channel.

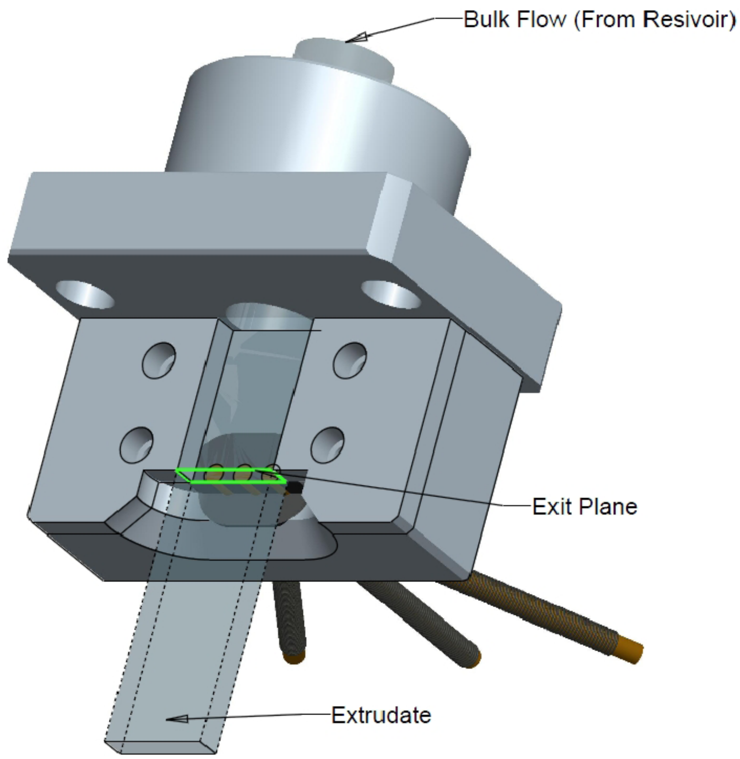



**Figure 6- Cutaway of extruder die (note cutaway in die head to ensure heater pins are last surface in contact with extrudate).**

### Resolution Constraints

Maximum resolution in both the extrudate direction and between temperature controlled channels is constrained by the physical limitations imposed by the separating insulator material, thermal time constant of each temperature channel, heat flux capabilities of heater pins, and thermal conductivity of the extruded material. As the thermal properties of the extruded material are unchangeable in this case, the design objective for an optimal solution would have perfect insulators between channels, minimum thermal mass and maximum achievable heat flux for each thermal circuit. A perfect insulator would allow maximum thermal gradients and minimize cross talk between channels. Larger achievable thermal gradients will allow for sharper transition between surface pixels and faster thermal response time allows for sharp transition between consecutive textured regions.

**System Design**

A number of additional design decisions are revealed, when the scope of the current thermodynamic system analysis is expanded to include the entire extruder apparatus (see Figure 7 for an image of the current extruder apparatus). In order to achieve predictable operation through the duration of an extrusion, a large mass of molten polymer must be maintained at constant temperature and flow rate. In the transition region between the polymer reservoir and the die exit plane a second temperature control region should be maintained to allow fine tuning of the extrudate flow before finally coming in contact with the individual thermal zones near the die tip. A temperature controller should be implemented that is capable of rejecting disturbances such as changes in local ambient temperature. The entire thermal system should be designed for maximum thermal isolation between elements to avoid cross talk between the single-input single-output (SISO) controllers.

**Figure 7- Extruder apparatus**

**Thermal control of rear die surface**

Making provisions for controlling the front and rear die surfaces independently would allow extrusion with a glossy back surface which may simplify imaging of the resultant extrudate. As this aesthetic element is unnecessary for initial conceptual testing, back surface temperature control was initially accomplished by regulating the temperature of the entire heater die. This compromise simplifies the initial die design at the expense of imaging clarity (see Figure 8 for an example of sharkskin image clarity).

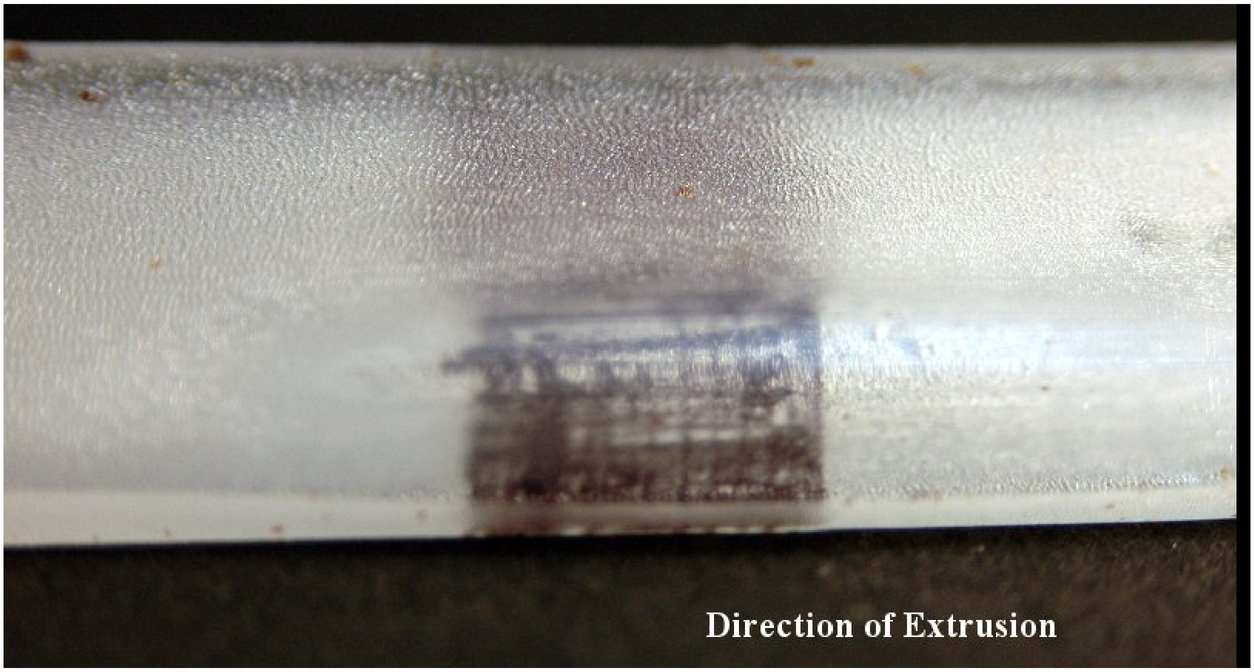



**Figure 8- Gradient in sharkskin amplitude across extrudate surface.**

## Design for Manufacturability

After identifying thermal and physical system constraints, it became clear that manufacturability would be the limiting factor of any extruder die design. Instead of designing for optimal thermal performance characteristics, some concessions were made to allow for ease of machining and assembly. The extruder head was designed as an assembly to allow for ease of upgrading components or changing extrudate dimensions without requiring an entirely new die design. The modular component design affords a level of flexibility in heater block dimensions as subsequent thermal design optimizations can be easily implemented by swapping out the heater block.

A number of techniques were tested to determine a practical method for producing heater components of the highest performance. One rudimentary technique involved using flat conductors between insulation plates of Teflon or ceramic.  Due to the small dimensional features required to produce multiple temperature zones across a small extrusion region, accurately assemble became prohibitively difficult. Another method involved embedding pin heaters within an epoxy-type resin. This approach afforded the opportunity to attach temperature sensing devices near the surface of the heater pin, while providing better dimensional tolerances than achievable in assembled Teflon devices. Several resin materials were evaluated as possible options before ultimately settling on JB Weld due to its acceptable thermal conductivity, dimensional tolerances, ease of machining, and finishing properties. See tableref for the performance of each insulator material.

**Heater Pins**

Several manufacturing experiments were conducted to determine the most viable heater pin geometry. Commercially available cartridge heaters were quickly eliminated due to their relatively large diameter, and inaccurate tolerances near the heater tip. Cylindrical pin heaters can be made to nearly any diameter and can be easily wrapped with resistance heater wire to create a custom geometry. After settling on a cylindrical geometry, 30 Awg Ni-Chrome wire was selected as the resistance heating element for this device so that the dynamic range of readily available 0-30Vdc power supplies could be utilized. A number of options for heater construction methods are outlined in Appendix A.

**Incorporating Temperature Measurement**

A method for ascertaining surface temperature of heater pixels is critical for process control. Knowing the actual surface temperature would allow for better quantification of experimental results and would allow for eventual closed loop control of the printing process. For simplicity, a temperature measurement device could be embedded in the die near the surface in contact with the extrudate. An ideal temperature measurement device would be of negligible thermal mass, and could be placed at the measured polymer surface. Thermocouples and RTDs require an additional signal conditioning device to interfaces with a data logging apparatus. The additional cost of dedicated equipment is unjustified for this application and beyond the initial budget allocated for this project.

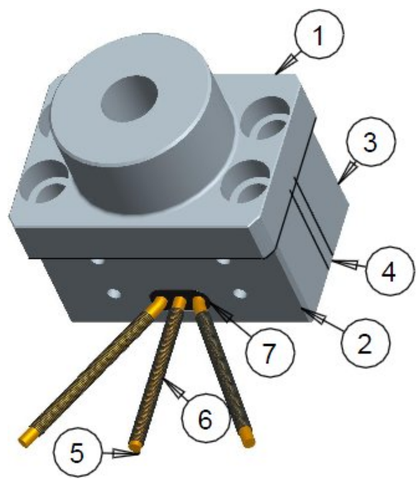



**Figure 9- Multi-channel extruder die assembly: 1)Inlet block 2)Front heater block 3)Rear heater block 4) Spacer to set extrudate thickness 5) Heater pin 6) Heater coil**

LM35 Temperature ICs proved to be the ideal solution for initial development. These chips offer a measurement range of 0-125C with 0.1degC accuracy. They can be easily interfaced with my existing temperature logger apparatus, and were relatively inexpensive at $0.23 each. The 0-5vdc analog output of these chips has the added benefit of easy integration into a microcontroller for closed loop control applications without additional signal conditioning electronics.

## Heater block construction

A technique was developed for simply producing multichannel heater block elements. Initially a base block of aluminum is machined to will accept heater pins and insulator material. Next, LM35 temperature sensors are epoxied to brass heater pins. 30Awg insulated conductors are soldered to the temperature sensor pins (Red 5vdc, White- Gnd, Blue- signal). The heater pins are then inserted into a spacer jig, and are optically aligned with the aluminum base block using a microscope (see Figure 10 for the alignment assembly).

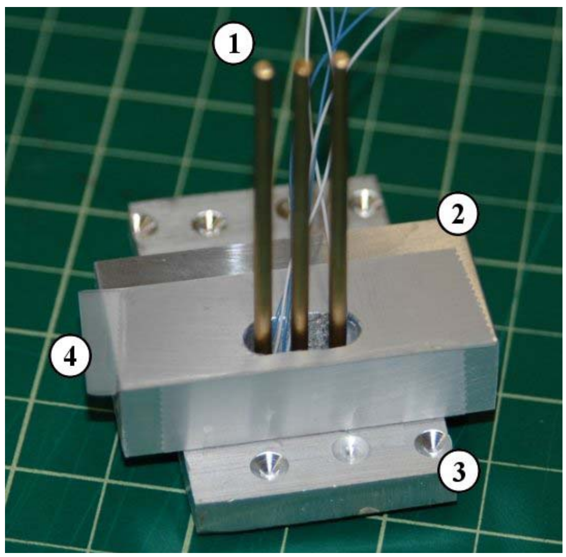



**Figure 10- Heater block assembly jig before pouring epoxy: 1) Heater pin, 2) Heater block, 3) Pin alignment jig, 4) Scotch tape used as epoxy release**

The alignment jig also ensures that the base of the temperature sensors lie 0.01” above the extrudate contact surface plane. After the pin and sensor orientation is rechecked, JB Weld epoxy is carefully poured into the base block cavity. To reduce the chance of bubble entrapment in casting features, the entire assembly is placed in a vacuum chamber (20mm Hg) for 2min to degas the epoxy. After the epoxy is allowed to harden for two days, the pin alignment jig is removed. Subsequently the extrudate contact surface of the heater block is machined and polished to remove the portion of the heater pins used for alignment purposes. After assembly, the heater block is machined so that the heater pins are the last thermal element in contact with the extrudate (see Figure 6).

**Technique Limitations**

Although the aforementioned technique allows for production of precision heater elements, it is difficult to produce heater pins with temperature sensors smaller than the 600 series surface mount device form factor due to difficulty associated with soldering loose leads to component contacts (Figure 11).

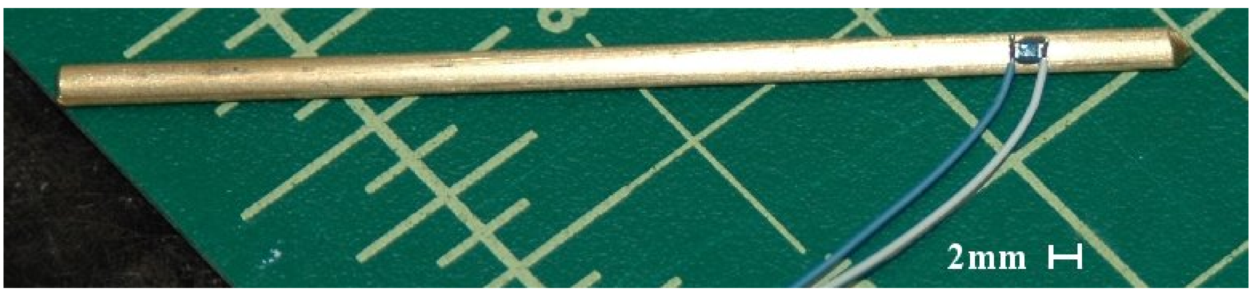



**Figure 11- 600 series surface mount RTD epoxied to heater pin and soldered to leads.**

Due to the irreversible nature of cementing heater pins in place, care must be taken to ensure that temperature sensors are functional prior to pouring the insulator casting. Following successful temperature sensor testing, 30 Awg 24 Ohm (+- 1 Ohm) heater coils are wound onto the heater pins using specially made tool (see Figure 12). A layer of high temperature tape is used as an electrical insulator between the brass heater pins and the bare Ni-chrome wire. The layer of tape furnishes the added benefit of separating adjacent turns of heater wire thereby reducing the potential for shorting coils across each other during operation. A shorted turn of heater wire would reduce the total resistance of the heater coil by dR=Rcoil/N where Rcoil is the total coil resistance and N is the total number of coil turns.

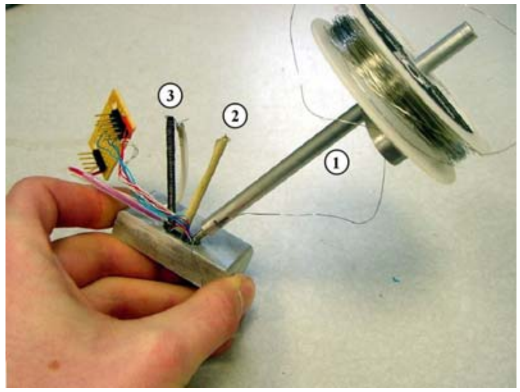



**Figure 12- Demonstrating custom coil winding tool: 1) coil winding tool 2) High temperature insulation tape 3) Completed coil**

## Calibrating Temperature Sensors and Thermal Models

### Temperature Sensor Calibration

A three point calibration was performed to characterize the LM35 temperature sensor ICs. Each temperature sensor was connected to a separate channel of an analog-to-digital converter. The entire heater block (see Figure 13) was immersed into a well stirred water bath and allowed to equilibrate at 70, 80, and 95 deg C. Slope and offset calibration coefficients were calculated for each temperature sensor.

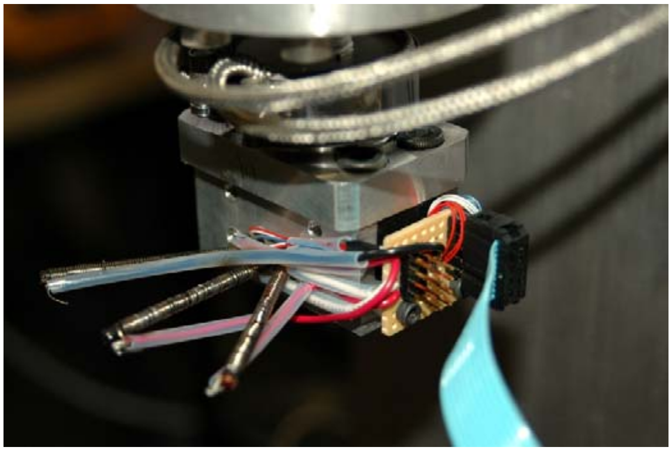


**Figure 13-Three channel extruder die with integrated temperature sensors.**

## System Identification

A regression based system identification method was employed to determine model coefficients for the extruder die thermal system. Experimentally identifying a representative system model obviates the need to determine the exact values of physical parameters such as heater pin and coil heat transfer. By eliminating the need for determining exact component values, it is possible to increase the overall accuracy of the resultant system approximation by reducing propagation of measurement error. The heater coil was subjected to a range of step voltages (12-24Vdc) to gain an understanding of heater dynamics across the entire operating window. During all tests, the heater block was installed into the extruder die assembly and the reservoir and transition region heaters were held at their usual operating temperatures of 110 and 85 deg C respectively. The coefficients of first and second order system models were tuned to closely approximate the actual recorded data (see Figure 14). It was determined that a 1$^{st}$ order approximation was sufficient to approximate the system dynamics observed in the heater pin thermal system. The resultant system approximation was used in subsequent thermal simulations of the heater die assembly.

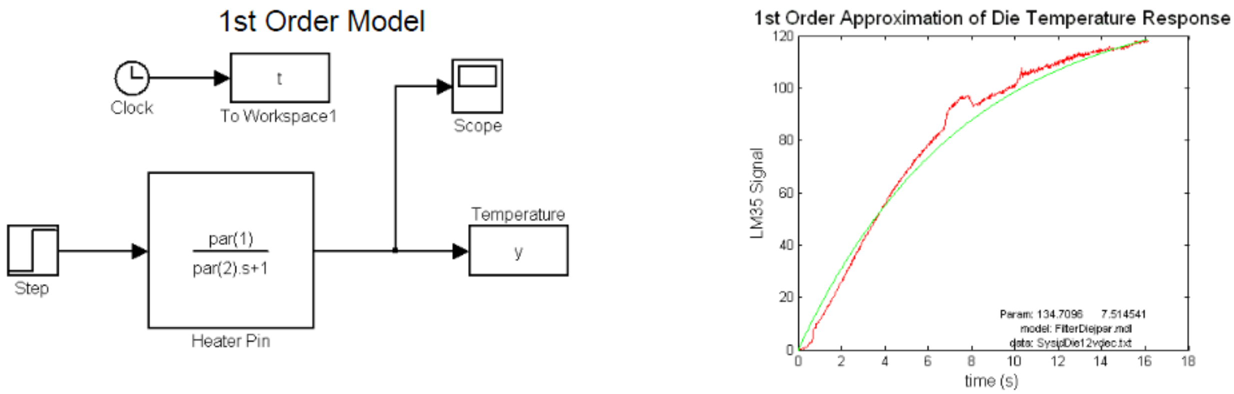



**Figure 14- Regression Based System Identification. Left) 1st order approximation of thermal system. Right) Results of system identification. The red line represents temperature data, and the green line represents the output of the tuned system model.**

### Finite Differences Thermal Approximation

A finite differences approximation of die thermal characteristics was developed to simulate the thermal operating conditions encountered by the extrudate at the die exit plane. The die was approximated as one dimensional heat transfer with known wall and pin temperatures and unknown insulation temperature (see Figure 15 for a diagram of boundary conditions).

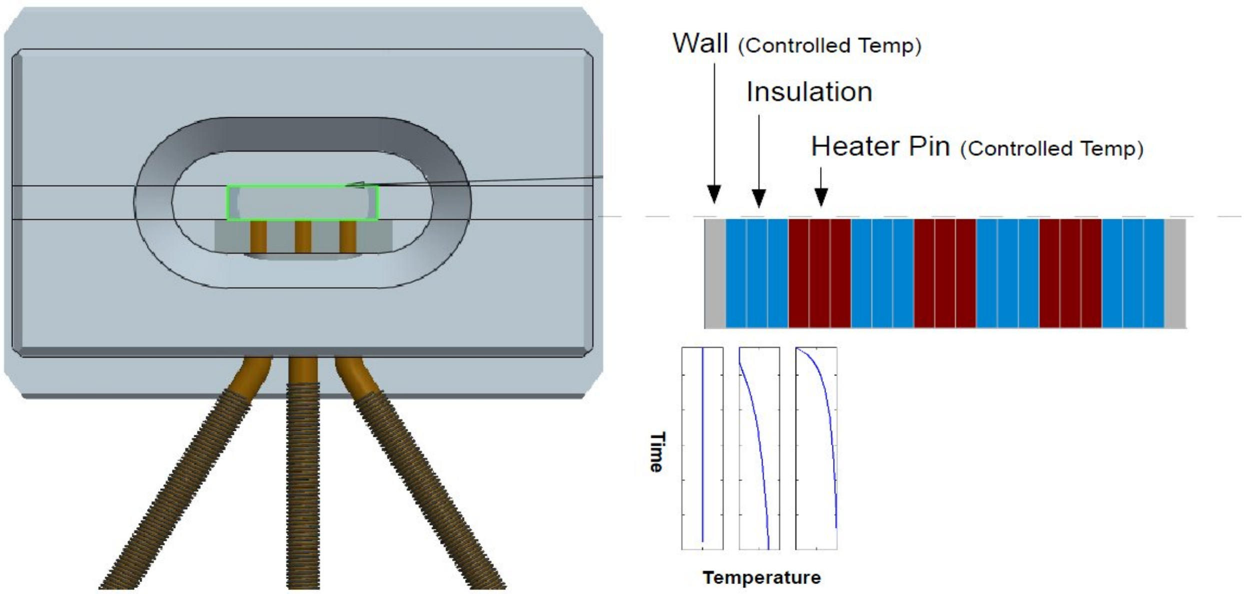
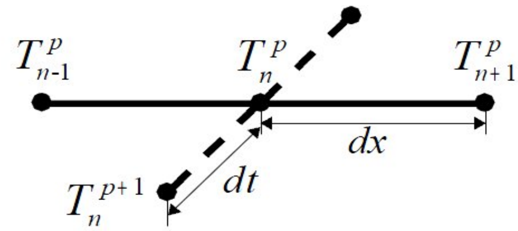



**Figure 15- Boundary conditions used in finite differences approximation.**

A one dimensional model is sufficient for initial thermal analyses due to the symmetric nature of the analyzed region and comparatively small out of plane losses. It is possible to approximate the temperature dynamics encountered at the heater pin tip by applying the thermal model as tuned in the initial system identification. The finite differences approximation was initially developed as a diagnostic tool for tuning the closed loop feedback controller. By utilizing the finite differences system analogue, controller designs could be quickly evaluated without requiring the time associated with preparing a fully loaded extruder barrel for each test. The simulation was developed as a generic model to allow the addition of more complicated boundary conditions and thermal properties as modeling requirements change. For example, additional dimensions should be incorporated into the thermal model if the effects of convective heat transfer from the extrudate mass are to be accounted for. See Figure 16 for an illustration of the one dimensional finite differences model used in this simulation.




Fourier Number

$$Fo = \frac{\alpha \cdot dt}{dx^2}$$

Thermal Diffusivity

$$\alpha = \frac{k}{\rho\, C_p}$$

Stability Criterion

$$Fo \leq \frac{1}{4}$$

$$T_n^{p+1} = Fo\left( 2T_{n+1}^{p} - 4T_n^{p} - 2T_{n-1}^{p} \right) + T_n^{p}$$

**Figure 16- One dimensional finite differences approximation of extruder die.**

## Temperature Control

### Overall Control Scheme

For simplicity, extruder temperature control was separated into three independent zones. Three band heaters controlled by a commercial PI controller are used to maintain constant temperature of the upper barrel region. PI constants were adjusted to keep the mass of plastic at constant temperature with minimal set point overshoot despite changes in ambient laboratory temperature. The temperature of the die inlet region is controlled by a separate commercial PI controller so that the main die is held at a constant temperature independent of the reservoir region. Temperature regulation of this region can be utilized as a transition zone between the main reservoir temperature and the final output plane temperature. The temperature of each heater pin can be controlled separately so that individual pixels of sharkskin can be produced at will. By changing controller settings, it is possible to implement both open and closed loop control schemes on the multi-heater zone test apparatus.

**Three Pixel Font**

A character set (see Figure 17 left) was developed in order to demonstrate transient and steady state control of heater pin elements. A font was designed that utilizes the three heater pins of the current heater design. As noted in the test phrase below (Figure 17 right), words are clearly legible despite the low resolution afforded by three pixels. Readable characters offer an interesting proof of concept as they incorporate a number of challenging test conditions for a specific heater die design. For example, printing an “M” requires exacting transient control so that the entire character can be reproduced without awkward separation regions. Printing a character such as “H or “O” requires tight temperature control to avoid regions of texture bleeding between pixel elements. The character set will stand as a benchmark to gauge the effectiveness of subsequent heater control schemes.

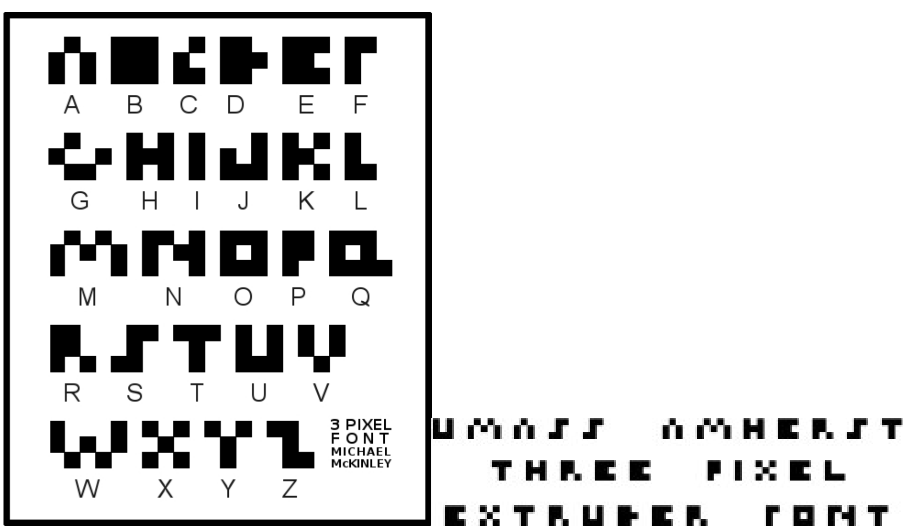



**Figure 17- left) Three pixel extruder font. right) Test phrase for font legibility.**

### Character Generation

In order to accurately reproduce characters, a sequence of commands must be sent to the heater pins at defined intervals. An interpreter program was developed to automate the process of producing the controller set point commands necessary to reproduce each character. The program was written so that a desired text string can be inputted and a required set points and delays are outputted as TTL voltage commands to the computer's parallel port. The set point generation algorithm was developed as a modular component to the extruder controller. Algorithm modularity ensures that software components can be easily reused without major design changes as the extruder apparatus is upgraded.

### Heater Coil Control Board

Relays were utilized to control the voltage source for each heater coil. An interface board was designed to drive 12vDC heater coil relays from a 5vdc TTL output (e.g. parallel port or microcontroller). An isolation diode was incorporated into the controller board as protection against the induced voltage spike associated with operating the relay coil. Relays offer a means of electrically isolating the heater coils from the command generation device, and make it possible for a variable laboratory power supply to be easily connected to the heater pins. Electrical isolation adds an additional level of safety against accidentally destroying command and measurement computers through operator error. See Appendix A for a schematic and bill of materials for the relay interface board.

**Rudimentary Open Loop Heater Pin Control**

A rudimentary open loop heater pin control scheme was developed as a proof of concept. The character generation algorithm was configured to produce set point commands at a frequency linked to the extrudate flow rate. Appropriate heater duty cycles were estimated using the thermal model developed from initial system identification. Accurate knowledge of the thermal time constants associated with each heater pin is critical to providing enough time for heating and cooling of the die pins. Before attempting to print characters with the extruder, the test was first simulated with the finite differences approximation (see Figure 18). Finally the extruder was connected to the relay control board and characters were successfully printed see Figure 19.   See Appendix D for a diagram of the open loop control scheme.

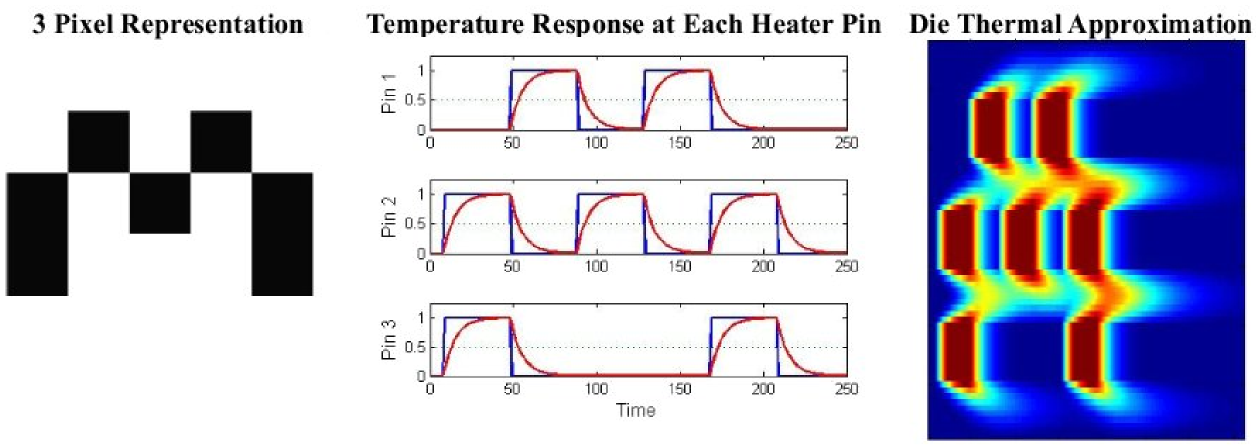



**Figure 18- left) Desired character. center) blue- Command temperatures. red-thermal response of heater pins. right) Estimated temperature response of extruder die**

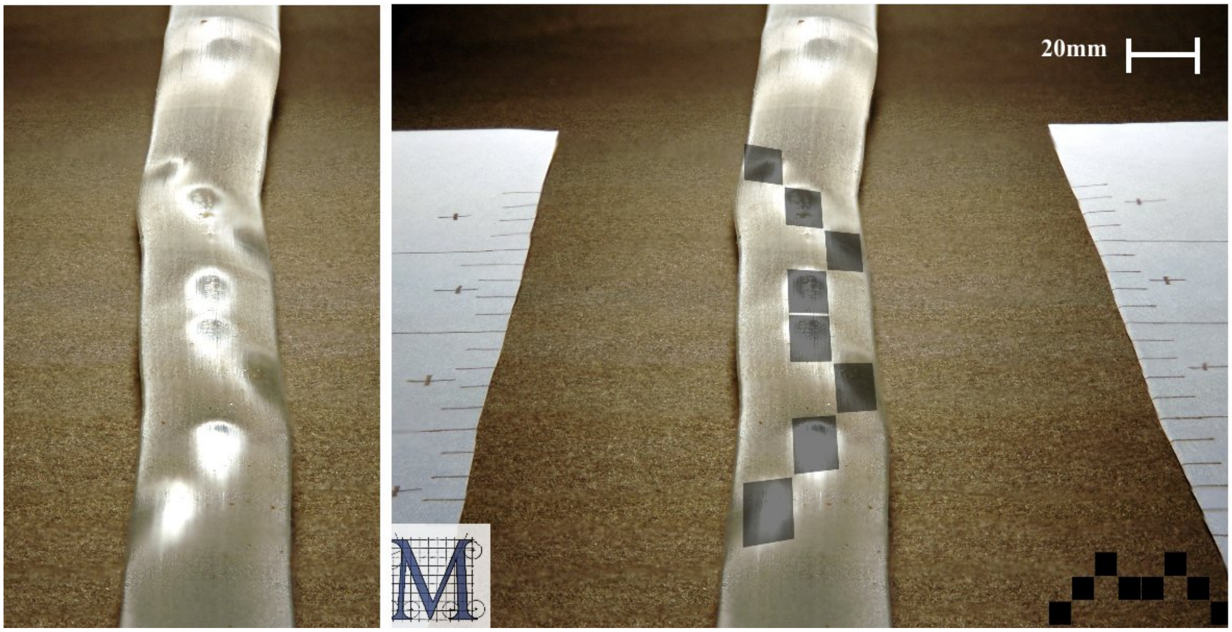



**Figure 19- left) Extruded "M". right) Note correlation to desired character.**

## Implementing Closed Loop Control

It is possible to realize gains in extruded character resolution by adding a closed loop heater pin controller. Closing the loop is a simple matter of designing a controller board to operate between the set point generation algorithm and the relay control board as used previously. The embedded LM35 temperature sensors (in the heater die) were connected to a microcontroller's internal 10 bit A/D converter. Each temperature control loop receives set point commands as digital TTL signals from the character generation algorithm. The heater coil relays are controlled by 2Hz pulse width modulation (PWM) through the microcontroller's 8bit analog pins. A three channel PID algorithm was written for the microcontroller to read heater pin temperature data at 40hz and adjust relay parameters as necessary. See Appendix E for a diagram of the closed loop control scheme and Appendix F for a schematic and specifications of the microcontroller breakout board.

### Controller Tuning

A closed loop controller test apparatus was constructed to expedite the controller tuning procedure (as shown in Figure 20). This apparatus makes it possible to use low thermal mass components (see Figure 21) to save time in the process of debugging controller algorithms. After demonstrating algorithm functionality, a model of the extruder die is connected to the system for subsequent tuning (as illustrated in Figure 20). Although not completely representative of the actual extruder apparatus, the die analog allows for quick adjustments of the controller tuning code without disturbing the main extruder apparatus (left setup in another lab). After recording test data, a Gauss-Newton regression algorithm similar to the Iterative Feedback Tuning (IFT) method described by Hjalmarsson et al (1998, 2002) was used to optimize each heater controller. Upon finalizing tuning procedures, the microcontroller board was removed from the test apparatus and re-tuned for optimal extruder performance. See Appendix G for a brief explanation of regression based controller tuning.

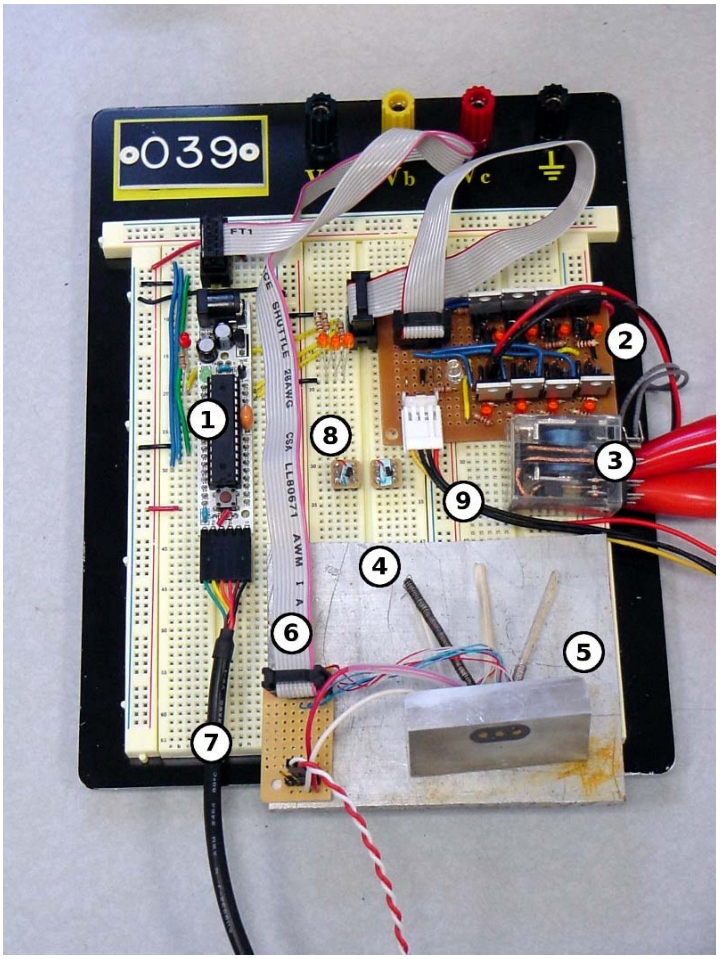



**Figure 20- Closed loop controller test apparatus: 1)ATMEGA 168 MCU, 2)Relay interface board, 3)12v Relay, 4)Heater pin with 30Awg coil, 5) Heater block assembly, 6)Output from temperature sensors, 7)RS232 data cable**

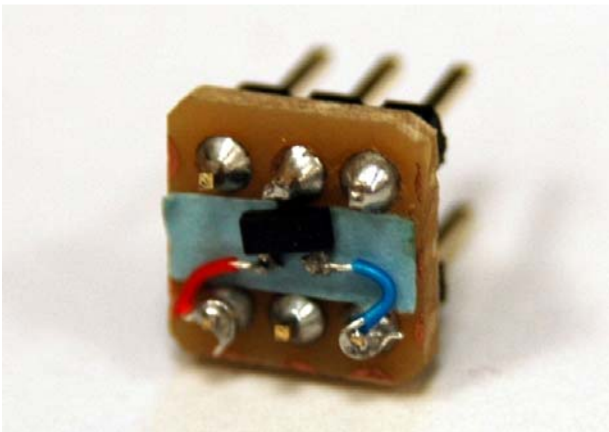


**Figure 21- Low thermal mass temperature sensor used for debugging.**

## Results

The initial objective of controlling multiple sharkskin textures across a single surface has been successfully demonstrated. A method for producing multichannel heater dies has been developed and tested through the production of a number of functional die elements. After achieving the primary goal of this research, an electronic control system was designed and implemented so that the limits of resolution could be explored. As a proof of concept characters were printed using initial open loop control schemes. Additionally elements of a closed loop controller were designed and constructed for subsequent installation into the extruder apparatus. Finally, a rudimentary thermal simulation was developed as a diagnostic tool for predicting extruder performance.

## Future Work

Although a closed loop control algorithm has been successfully implemented and tuned for the thermal controller test apparatus, closed loop control has yet to be demonstrated on the plastic extruder itself. Newfound gains in resolution should be possible by carefully tuning control parameters to closely match the performance of the actual system. Furthermore, after attaining closed loop control an interesting study would be to determine the lower limits of controllable sharkskin amplitude.

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# Appendices

## Appendix A-Heater Assemblies from Various Materials and Methods

Flat strip Teflon sandwich heater

Easily disassembled Difficult reassembly

Difficult to maintain dimensional tolerances

Difficult to embed temperature probes close to outlet surface

Embedded heater

Embedding compounds

Epoxy

Lowest viscosity- easy to flow into crevices before hardening

Quick set time

Poor thermal properties -discoloration and deformation when heated

Poor hardness

Poor surface polish

Ceramic Epoxy

Excellent thermal stability/ insulation

Poor adhesion to smooth surface (machined surface finish)

Large grains make for poor details (small radius regions)

Poor surface polish

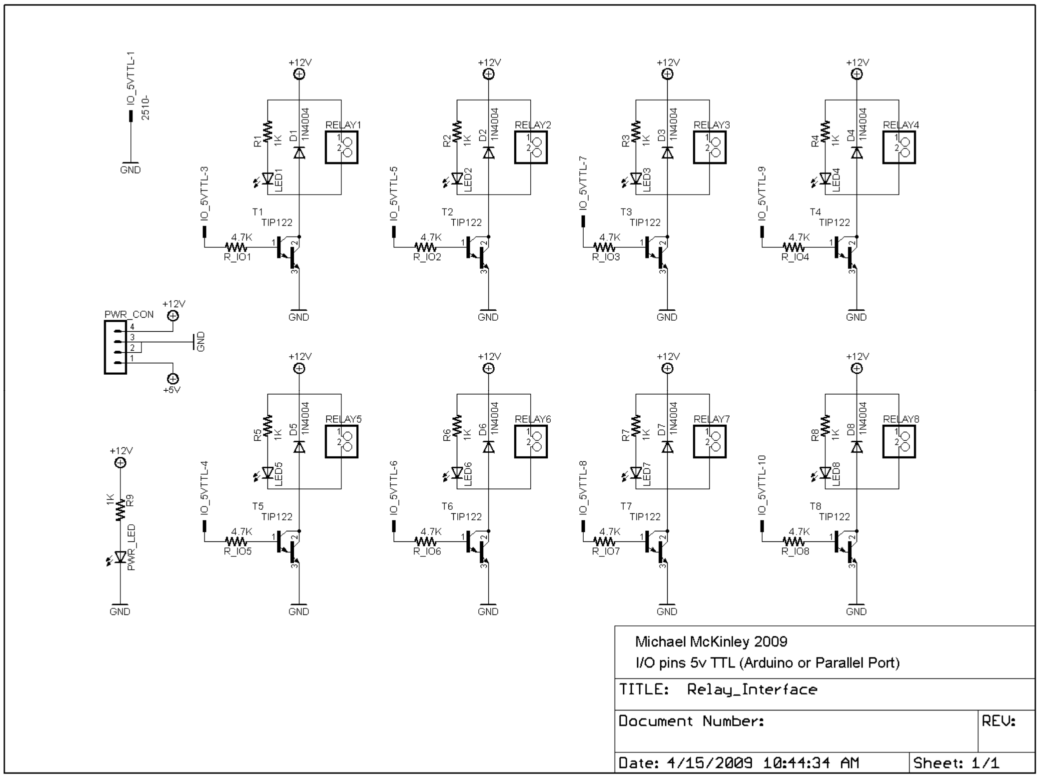
JB Weld

Acceptable thermal stability within operating range

Poor thermal resistance (when compared to teflon or ceramic)

Higher viscosity than Epoxy (must carefully removal of bubbles)

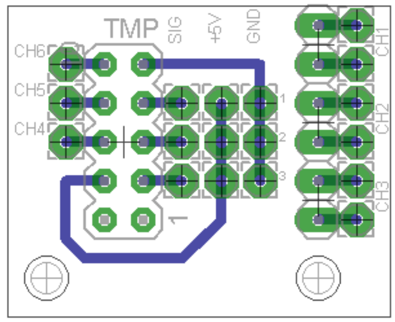
## Appendix B-Relay Interface Board: Schematic and Bill of Materials

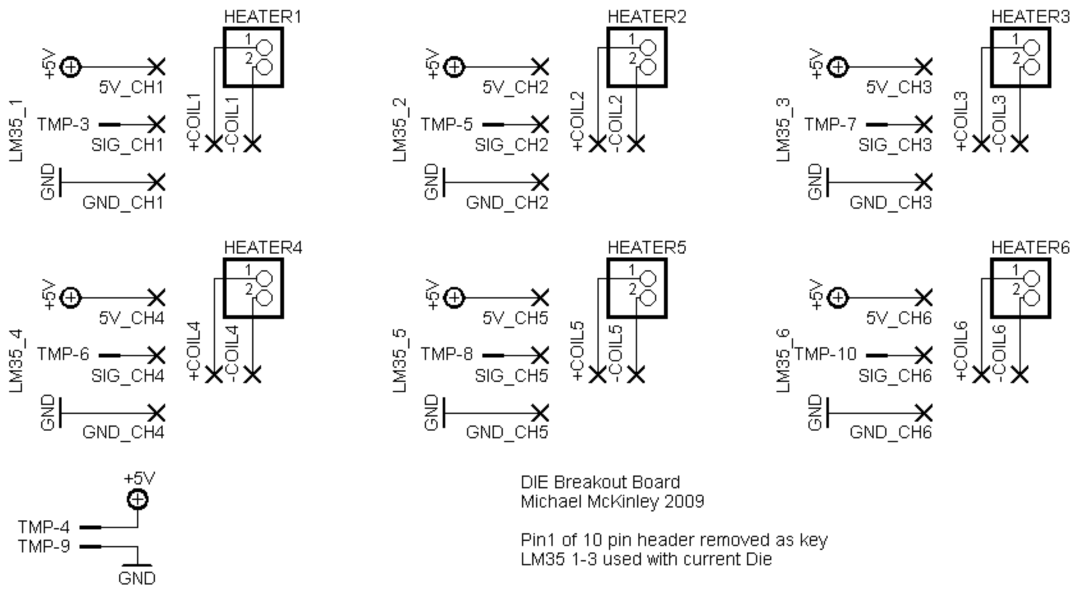



**Relay Interface Board: bill of materials**

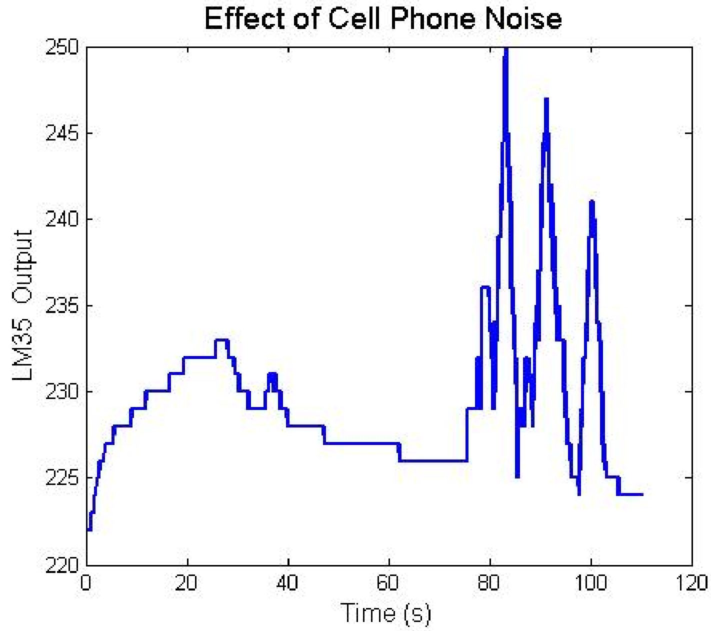
| Part | Value | Device | Package |
|---|---|---|---|
| D1-8 | 1N4004 | Diode | D041-10 |
| IO_5VTTL | | 0.1” Header | PAK100/2500 |
| LED1-8 | | LED3mm | LED3mm |
| PWR_CON | MA041 | 0.1” Header | |
| PWR_LED | | LED3mm | LED3mm |
| R1-9 | 1K | resistor | 0207/7 |
| RELAY1-8 | | 12vDC relay | |
| R_IO1-8 | 4.7K | resistor | 0207/7 |

**Appendix C- Temperature sensor board (attached to extruder die): PCB design and Schematic**

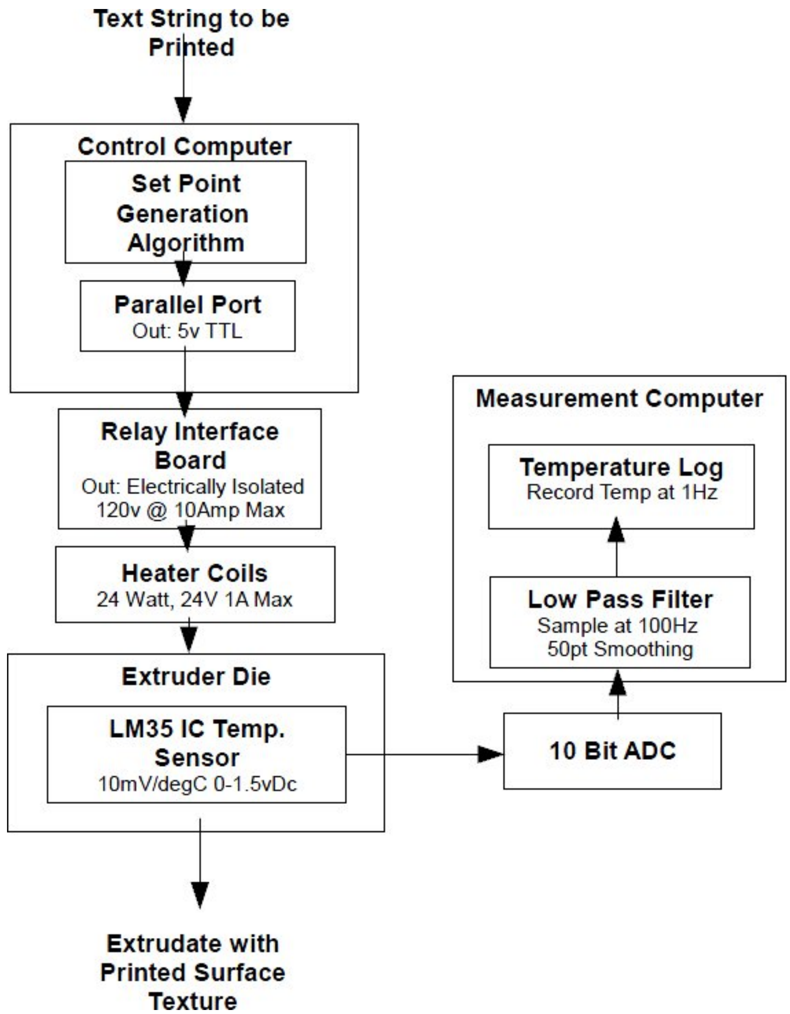


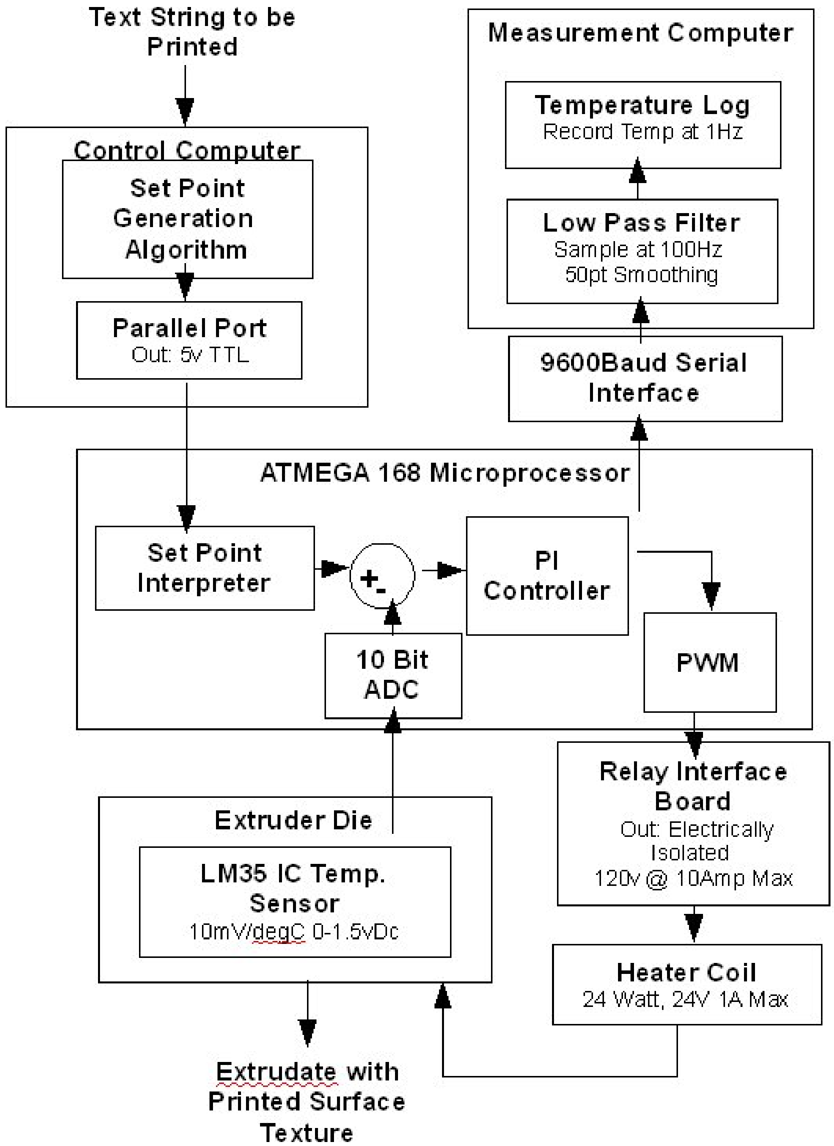
**Appendix D- Effect of cell phone noise on unshielded transducer channel (note large interference spikes from 80- 100 seconds)**



**Appendix E- Open Loop Control Process Diagram**



## Appendix F- Closed Loop Control Diagram




Note: On Controller Stability

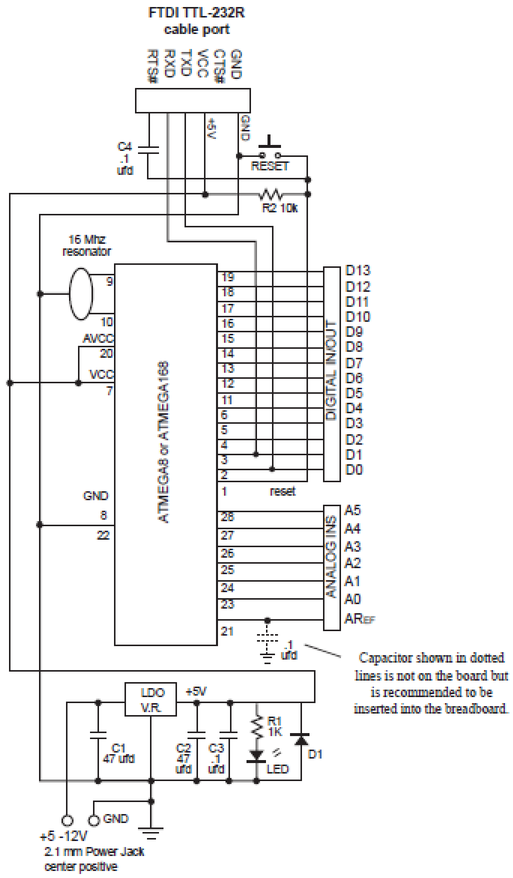
Stability Rule of Thumb

$$dt \leq \frac{\tau}{10}$$

Fastest Time Constant 3sec

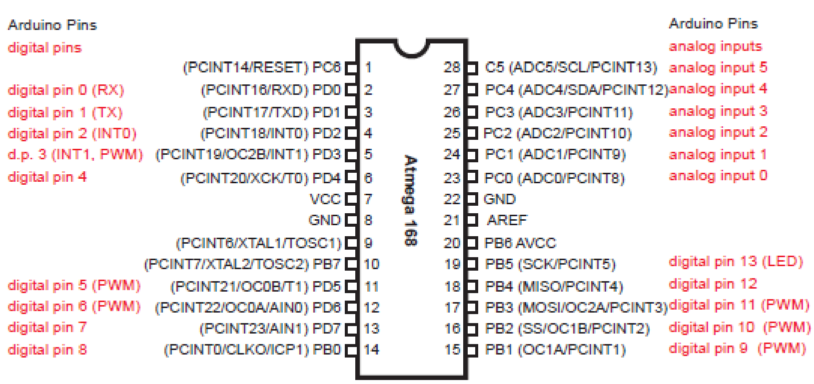
40Hz >> 3Hz

# Appendix G-RBBB Arduino schematic and AMTEL168 MCU Pinouts



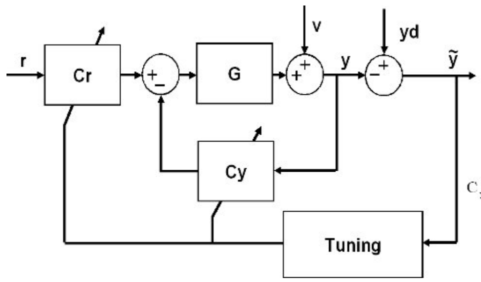

Real Bare-Bones Board / Board Schematic
RBBB
Arduino® - Compatible

RBBA/B Schematic
Unlike some other Modern Device products, this schematic
and board design are in the Public Domain.
Paul Badger 10/2007




Pin mapping of the Atmega168 chip to the Real Bare Bones Board

**Appendix H- Regression Based Controller optimization**




$$\theta = [K, T_i, T_d]^T$$

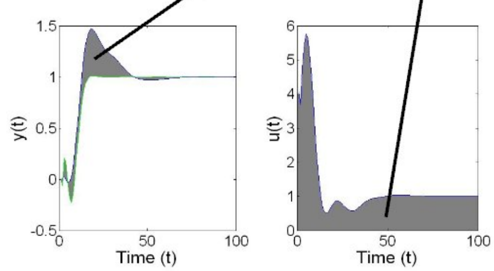
$$C_r(\theta) = K\left(1 + \frac{1}{T_i s}\right)$$

$$C_y(\theta) = K\left(1 + \frac{1}{T_i s} + T_d s\right)$$

Diagram of closed loop controller with external tuning algorithm.

Cost Function

$$J(\theta) = \frac{1}{2N} E\left\{ \sum_{t=t_0}^{N} \left(L_y \tilde{y}_t(\theta)\right)^2 + \lambda \sum_{t=t_0}^{N} \left(L_u u_t(\theta)\right)^2 \right\}$$




The initial controller data is compared to a desired system output to quantify controller performance.

Iterative Parameter Adaptation

$$\theta_{i+1} = \theta_i - \gamma_i R_i^{-1} \nabla J(\theta)$$

$$\theta^* = \arg\min_{\theta} J(\theta)$$

An iterative parameter adaptation scheme designed to minimize controller cost.