Electrical Design of Structurally Tunable Skin Overlays

by

Miren Bamforth

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Submitted to the Department of Electrical Engineering and Computer Science
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Author .................................................................

Department of Electrical Engineering and Computer Science
January 19, 2018

Certified by ...........................................................

Chris Schmandt
Principal Research Scientist
Thesis Supervisor

Accepted by ...........................................................

Christopher J. Terman
Chairman, Masters of Engineering Thesis Committee
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Abstract

Current on-skin interfaces focus on enabling electronic circuitry and display-like output on top of the skin, but to the best of our knowledge interfaces for tuning the texture or stiffness of the skin itself are unexplored. We present SkinMorph, a second skin layer that alters its texture and color due to attached electronic control circuitry. Modular electrical design of the system includes a bare-bones processor board with three optional, interchangeable, stackable peripheral modules: a programming and debugging module, a Bluetooth module, and an accelerometer module. The modular circuits in tandem with customizable silicone injection molds allow for adaptation to a variety of applications, resulting in a system which affords some physical protection via tuning the skin overlay characteristics on various areas of the body. Particular attention is paid to on-skin challenges such as electrical and heat safety, miniaturization of circuit components, and skin-safe material choices. The entire system including battery, control board and peripherals, and tunable skin overlay can be mounted on the body without a wired tether impeding the user.

Thesis Supervisor: Chris Schmandt
Title: Principal Research Scientist
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Chapter 1

Introduction

On-body technologies are pervasive in modern society, from medical devices inside the body to smartwatches outside the body. On-skin interfaces are a new category of on-body technology as presented in Figure 1-1. This category marks a progression from rigid devices sitting against the skin toward devices placed directly onto the skin. These on-skin interfaces are an active research area, particularly in the Human Computer Interaction (HCI) field. However, to the best of the researchers’ knowledge, no existing on-skin interfaces explore dynamic tuning of skin texture or stiffness.

Figure 1-1: On-body technologies (from [27]).
This thesis presents SkinMorph, a novel on-skin device with tunable stiffness properties and modular electronic control circuitry. The system consists of customizable, injection-molded silicone skin overlays filled with hydrogel, a material whose stiffness, color, and thermal characteristics can be manipulated. These silicone skin overlays are embedded with nichrome wire heating elements which connect to the modular control circuitry. SkinMorph can be programmed to activate stiffness tuning upon input from the wearer over a Bluetooth connection, after a switch toggle, or due to certain movement detected by an accelerometer. The stiffened material provides haptic feedback to the wearer while affording some amount of protection. Qualitative and quantitative analyses are provided in the thesis.

1.1 SkinMorph Overview

SkinMorph is an on-skin device with two major components: modular circuitry and silicone skin overlays. Figure 1-2 displays a processor board named Morphio attached to an Accelerometer Module and a Bluetooth Module. These modules are not required for SkinMorph to function; only the Morphio is essential. A Programming Module also exists. These three modules can be mixed and matched with the Morphio as appropriate for the application.

Figure 1-2: An example of the modular circuitry of SkinMorph. A Morphio processor board sits below an Accelerometer Module and a Bluetooth Module.
The other primary component of SkinMorph is the silicone skin overlay. Figure 1-3 provides an exploded view of the layers within a square silicone skin overlay. The resistive heating traces raise the temperature of the hydrogel to tune its stiffness. The shape of the silicone overlay determines the form factor of the device, as the hydrogel adapts to whichever shape encapsulates it. The placement of the skin overlay and the purpose of that placement determine the appropriate form factor. The entire assembly adheres to the wearer’s skin with skin-friendly adhesive designed for the special effects makeup market.

Figure 1-3: An exploded view of a silicone skin overlay.

The resistive heating traces of each silicone skin overlay connect to a Morphio. The Morphio can then electrically control the hydrogel’s stiffness. The peripheral modules attached to the Morphio determine how the stiffness is tuned. For example, a Morphio with a Bluetooth Module may increase the stiffness when instructed to do so by a message received over Bluetooth from the user’s phone.
1.2 Thesis Motivation and Contributions

The objective of this research is to provide proof of concept for a stiffness-tunable skin overlay by combining previous research in soft materials [31] and on-skin electronics [20]. The deliverables include multiple functional demonstration systems, a paper to be published, and a demonstration video.

The objective of this thesis in particular is to design, fabricate, and test the electrical subsystem. The following iterative process describes the bulk of the thesis work: collection of electrical subsystem requirements from other parts of the system such as changes in material choice; circuit design, including component specification; schematic creation; printed circuit board (PCB) layout including component footprint creation; generation of fabrication files; PCB assembly by hand with a reflow oven; circuit testing; system integration including composition of necessary firmware; and, finally, system testing. Design requirements changed in response to system testing, spurring a new round of iteration.

1.3 Thesis Structure

Chapter 1 outlines the motivation and individual contribution of this thesis as well as the project as a whole.

Chapter 2 provides background information regarding various fields relevant to this thesis. These fields include on-body technologies, joule heating, hydrogel and material science, and aesthetic design.

Chapter 3 describes the electrical design of the system. First, system-wide constraints are discussed. Then, the design, constraints, assembly, and testing of the Arduino-compatible Morphio, the Programming Module, the Bluetooth Module, and the Accelerometer Module are discussed. Additionally, design of the nichrome heating elements is covered in this chapter. Finally, evaluation of the electrical system is presented.

Chapter 4 explores the material choices and hydrogel implementation. Evaluation
of the altered hydrogel composition is included.

Chapter 5 covers the mechanical design and the workflow for creating an application demonstration. It includes instructions for placing the system on the user’s skin and operating the device.

Chapter 6 details the applications explored as demonstrations of SkinMorph. These applications include one for the heel, one for the elbow, and one for the wrist. A fourth application shows an aesthetic design for personal expression.

Chapter 7 concludes the thesis. Limitations and possible future expansions to the project are discussed.
Chapter 2

Background

This chapter provides the wide range of background information required to understand this thesis; SkinMorph as a research project fits into the field of HCI, but it draws upon elements from electrical engineering, mechanical engineering, material science, and design. While each element of SkinMorph has been explored before, this specific combination of these fields is novel. This chapter discusses the relevant parts of each field.

2.1 On-Body Technologies

This section covers the on-body technologies relevant to SkinMorph but does not provide a full review of the field.

2.1.1 On-Skin Interfaces

The field of wearable electronics has moved beyond rigid wearables which sit on the skin (but do not take advantage of the skin as a medium) to so-called on-skin electronics which progress towards seamless integration of interfaces on the body. On-skin electronics consider the skin and its characteristics during the design process and result in devices which rely upon the skin as part of the system.

Recent explorations present the skin as a medium for electric circuitry [9, 20, 49]
and display-like outputs [21, 28]. Wireless devices such as Near Field Communication (NFC) circuits may be placed on the skin as conformable, as opposed to rigid, form factors [20, 23]. Other work has explored the extent to which on-skin electronics pose fabrication and control challenges due to the unconventional medium [25]. Another category of research utilizes on-skin electronics for wireless medical data collection [2, 12].

As on-skin interface research has progressed, the devices have decreased in thickness and increased in seamlessness to the skin. iSkin, a skin overlay for touch sensing, was the first on-skin sensor for controlling mobile devices, although the thickness at 700 \( \mu \text{m} \) did not create a seamless interface to the body [49]. Further work created interfaces thinner than 100 \( \mu \text{m} \) which is enough to seem imperceptible to the wearer as posed by Kim et al [22]. Skintillates displayed input and output capabilities at 36 \( \mu \text{m} \) [28], and DuoSkin displayed input, output, and radio frequency capabilities at 30 \( \mu \text{m} \) [20].

Importantly, all prior work uses electronics on the skin in one of three modalities: as an input to an external device, an output usually in the form of on-skin visual display, or an RFID tag or similar wireless device. For SkinMorph, we seek to build upon previous epidermal electronic work to change the stiffness or texture of the skin as a device which has not been explored to the researchers’ knowledge.

2.1.2 Thermal On-Body Technologies

SkinMorph uses heating elements upon the body to control the stiffness of the skin overlays. Previous work in electrical control of thermal elements against the skin includes ThermoVR which placed Peltier elements against the face [15] and immersive SCUBA diving which placed Peltier elements against the wrist [35]. Both of these applications explored hot and cold stimuli for virtual reality experiences. Another thermal device is the Embr Wave, a bracelet which uses conduction through a heating and cooling plate to heat and cool the wearer [7].
2.2 Joule Heating

The temperature control technique which best fits SkinMorph’s system requirements is joule heating. Joule heating refers to the intentional use of the energy released when electrical current runs through a resistive material. This energy is dissipated in the form of heat as opposed to light or vibration. Most circuitry is designed to minimize the amount of energy released as heat because this heat goes unused in a typical application, wasting power and therefore causing the system to be less efficient. However, some applications purposefully create excess heat to be used for control of some temperature-dependent task. SkinMorph’s resistive heating element outputs heat when desired to control the tunable stiffness layer of the system.

Prior work in joule heating emphasizes thin trace serpentine routing for self-folding robots [10], shape-changing thin-film composites [13], and thermochromic on-skin displays [20, 21]. Initially, SkinMorph used thin trace serpentine routing of copper traces, but a variety of design decisions resulted in a switch to nichrome wire.

2.2.1 Nichrome Wire

Nichrome wire, an alloy of nickel, chrome, and sometimes iron, has commonly been used as a resistive heating element for decades [36]. Table 2.1 gives numerical values to compare the characteristics of nichrome and copper. This table includes the two most common types of nichrome wire used; SkinMorph uses NiCr 80, a combination of 80% nickel and 20% chrome.

<table>
<thead>
<tr>
<th>Property</th>
<th>Copper</th>
<th>NiCrA (NiCr 80)</th>
<th>NiCrC (NiCr 60)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>100% Cu</td>
<td>80% Ni, 20% Cr</td>
<td>61% Ni, 15% Cr, 24% Fe</td>
</tr>
<tr>
<td>Resistivity (nΩ * m)</td>
<td>17.2</td>
<td>319 [33]</td>
<td>331 [32]</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>1085</td>
<td>1400 [33]</td>
<td>1350 [32]</td>
</tr>
<tr>
<td>T.C. of Res. (per °C)</td>
<td>0.393%</td>
<td>0.011% [33]</td>
<td>0.015% [32]</td>
</tr>
</tbody>
</table>

Table 2.1: Comparison of copper and nichrome wires of varying chemical compositions. The resistivity is measured at 20°C. "T.C. of Res." stands for temperature coefficient of resistance.

The remainder of this section explains why nichrome is superior to copper in heating applications, including SkinMorph.
First, nichrome has a higher melting point than copper, so it can be raised to a higher temperature. SkinMorph does not operate above the melting points of either nichrome or copper, but other applications such as hot foam cutters [8], hairdryers [17], and industrial electric heaters [39] benefit from a higher melting point.

Second, nichrome has a lower temperature coefficient of resistance than copper. The temperature coefficient of resistance of a material describes how its resistance changes as its temperature changes as shown in Equation 2.1 (in which $\alpha$ is the temperature coefficient of resistance).

\[
R = R_{REF}[1 + \alpha(T - T_{REF})]
\]  

($R_{REF}$ is the resistance at temperature $T_{REF}$, and $R$ is the resistance at temperature $T$). A positive temperature coefficient of resistance means that as temperature increases, the resistance increases; a negative value means that the resistance decreases as temperature increases. A large temperature coefficient of resistance in either direction means that it is more difficult to design a system to work. For example, if a circuit is designed to output 1W of power across a resistor which is 100 $\Omega$ at 20 °C and has a temperature coefficient of resistance of 1% per °C, a change in temperature to 520 °C has the following effect on efficiency.

\[
P = V^2/R
\]

\[
1W = V^2/100\Omega
\]

\[
V = 10V
\]

\[
R = 100\Omega[1 + 0.01(520 - 20)] = 105\Omega
\]

\[
P = (10V)^2/105\Omega = 0.952W
\]

These example numbers result in a drop in power output of 4.8% which would be an unacceptable amount of deviation from the expected design in many cases. The difficult design challenges caused by a large temperature coefficient of resistance mean that nichrome’s lower temperature coefficient of resistance makes it superior to copper in applications which expect a large temperature change during operation.
Finally, nichrome has higher resistivity than copper, meaning that a copper trace of the same cross-sectional area as a nichrome trace must be longer than the nichrome trace to have equal resistance. This relationship is described by Equation 2.7.

\[ R = \frac{\rho L}{A} \]  

(2.7)

\( R \) is resistance, \( \rho \) is resistivity, \( L \) is length, and \( A \) is cross-sectional area. The inversely proportional relationship between length and resistivity (given fixed resistance and area) is apparent.

The reason that higher resistivity is desired is as follows. First, for a fixed amount of power output, current and voltage are inversely proportional since \( P = IV \). Given this relationship, the spectrum of circuit design choices for a specific power value ranges from a circuit with high voltage and low current to a circuit with low voltage and high current. However, a high current means larger traces, larger connectors, and potentially higher power losses within circuit elements. Furthermore, sourcing of components revealed more parts available for higher voltages with lower current than vice versa. Therefore, given a fixed power output value, a circuit with high voltage and low current is more desirable. Since \( V = IR \), a circuit with high voltage and low current requires a higher resistance. A high resistance value requires a short trace of a high resistivity material or a long trace of a low resistivity material due to Equation 2.7. For SkinMorph, the range of acceptable trace lengths and the set of desired resistances are such that the high resistivity of nichrome is highly preferable to the low resistivity of copper.

2.3 Material Science and Hydrogel

This section covers the material science relevant to SkinMorph but does not provide a full review of the field.

SkinMorph utilizes a custom hydrogel whose viscoelasticity is controlled through the manipulation of its temperature. This programmable change in viscoelasticity is a palpable, structural change in stiffness which is detectable when touched. It
also causes the hydrogels to transition from translucent to opaque. Hydrogels (i.e., hydrophilic gels) are formed by crosslinking, hydrophilic polymer chains that are extensively swollen with water, resulting in the substance’s gel-like consistency at rest. The strength and speed of reaction to the addition or removal of applied heat results from the composition of the hydrogels. Much research has gone into formulating stretchable yet tough hydrogels which mimic the mechanical properties of load bearing tissues in the human body to allow for practical hydrogel applications [26]. Stretchable hydrogel has also been explored as a medium for flexible electronics [50].

While structurally tunable on-skin electronics such as SkinMorph have not been previously explored, prior work has occurred with hydrogel-based devices as human-computer interaction (HCI) interfaces. Geltouch described three techniques of placing conductors inside hydrogel for use cases such as haptic keyboard feedback on a touchscreen display [31]. The material engineering for SkinMorph builds upon Geltouch and related thermoresponsive hydrogel as described by Wang et al [46]. Alternate methods of hydrogel synthesis include the specialized liquid printing explored in xPrint [48].

Hydrogel is skin-safe which makes it suitable for SkinMorph’s on-body applications.

2.4 Aesthetic Design and High Fashion

Prior work from SkinMorph’s lab group has demonstrated the intersection of functionality and aesthetics [18, 19, 20, 21]. SkinMorph follows this design philosophy: as an on-skin device, SkinMorph serves as an expression of self while being an extension of somatosensory capabilities [25].

The initial form factors explored by SkinMorph were inspired by Iris van Herpen’s injection molded haute couture designs as shown in Figure 2-1 [14, 45]. Figure 2-2 shows one of these couture-influenced silicone skin form factors.
Figure 2-1: The back of an injection molded design from Iris van Herpen’s 2017 collection *Between The Lines*.

Figure 2-2: A mannequin head with an early SkinMorph device on the cheekbone. The device is activated as evidenced by the opacity of the hydrogel. Two wire leads can be seen running from the left of the silicone skin to the back of the head; these attach to a hidden control board.
Chapter 3

Electrical Design and Implementation

This chapter begins with the overall and electrical system architecture to give context for the circuit design. Then, the family of Morphio boards and their designs are discussed. Next, design of the heating elements is presented. Finally, an evaluation of parts of the electrical system is given.

3.1 System Architecture

The SkinMorph device as a whole contains three primary sections which must work in collaboration: the circuit board controlling the device stiffness with or without peripheral modules, the power source, and the silicone skins filled with hydrogel and embedded with nichrome heating elements.

Figure 3-1: SkinMorph system architecture block diagram.
This thesis is concerned primarily with the blue blocks in Figure 3-1 which denote the control circuitry of the system. Although it is not the focus of this thesis, the design of the Silicone Skin subsystem is explained in Sections 4.1.2 and 5.1. The battery choice is discussed in Section 3.2.1.1.

SkinMorph has a modular design, allowing for applications of the system to harness various capabilities. All instances of SkinMorph must have a Morphio, the Arduino-compatible control circuit containing the processor chip and the bare minimum components to allow for the heating for the silicone skins. Figure 3-2 displays a more detailed block diagram of the architecture of Morphio.

![Morphio Architecture Block Diagram](image)

Figure 3-2: Morphio architecture block diagram. The Morphio serves as the primary control board of SkinMorph and has as few components as possible. For added capabilities, interchangeable peripheral modules can be connected.

Morphio has various input and output capabilities determined by which, if any, peripheral modules are attached, allowing for customization of SkinMorph for each application. For example, if the Accelerometer Module and the Bluetooth Module are simultaneously connected to the Morphio, the Morphio can send data to a user’s Bluetooth-capable device in real time to present the acceleration profile which caused the device to change its stiffness. More design choices about Morphio are described in Section 3.3, and application examples are available in Chapter 6.
3.2 System Design Constraints

This section discusses the various design constraints which the system must satisfy. The three primary categories of constraints are those which influence the final voltage choice of 5VDC, those due to the on-skin nature of SkinMorph, and cost.

3.2.1 Voltage Considerations

The system operating voltage is 5VDC. The following sections explain the variety of factors that led to this design decision.

3.2.1.1 Battery Technology

SkinMorph uses a Lithium Polymer (LiPo) battery as its power source. The primary concern was finding a battery which could be worn on the body. Due to their relatively thin profile, LiPo batteries were chosen. Additionally, low capacity LiPo batteries are cheap and readily available.

One challenge of using a LiPo battery was sourcing a battery that could discharge enough current. Many LiPo batteries with low capacity have a discharge rate of around 0.2C, which means a rate equal to one fifth of the total battery capacity. For example, a 1000mAh battery with 0.2C discharge rate can discharge 200mA continuously without veering into thermal runaway. Especially given the heightened safety concerns of a body-mounted device, care was taken to find a battery which could discharge enough current to meet the maximum power requirements of SkinMorph while keeping the battery as physically small (and therefore the capacity as small) as possible for ease of mounting the system to the body. These conflicting design constraints resulted in a battery of 1200mAh capacity with 0.9C discharge rate and dimensions 48mm by 30mm by 7.5mm as shown in Figure 3-3.

The choice of LiPo battery technology limits the range of voltages at which the system could run; this limitation is due to availability of appropriate parts as opposed to a physical limitation. LiPo batteries are 3.7V nominally, 4.2V when fully charged, and 2.8V when fully discharged. There are a variety of small form factor, surface
mount technology (SMT) power management integrated circuits (PMICs) designed specifically to output direct current (DC) voltage when powered by LiPo batteries in the 2.8V to 4.2V range. However, very few of these SMT PMICs are able to be output greater than 6V at a low price and small form factor. The price and size are the key limitations. Other systems may need to generate 12VDC from a LiPo battery, and they could, given enough space on the PCB and enough money. However, SkinMorph does not have financial or physical flexibility to allow for any chips outputting greater than 6VDC from a LiPo battery input.

Had a final voltage above 6V proven necessary, the system would have had to be redesigned. Fortunately, other system factors and constraints resulted in a final voltage choice of 5V. There simply is not market demand for the type of cheap, small SMT boost converters that are necessary for SkinMorph to operate at voltages higher than 6V.

### 3.2.1.2 Heat, Temperature, and Low Power

This section gives intuition regarding the amount of power necessary to generate the heat required to change the temperature of the silicone skins. Recall the specific heat equation.

\[ Q = mc\Delta T \] (3.1)

Q is heat in joules, m is mass of the heated object, c is the specific heat of the object,
and $\Delta T$ is the change in temperature. The hydrogel in the silicone skin must be heated from ambient temperature to its lower critical solution temperature (LCST), the temperature at which it changes stiffness. Heat and change in temperature are linearly related as seen in Equation 3.1. The heating element embedded in the silicone skin provides the heat to cause the temperature change. The provided heat must be great enough that the $\Delta T$ results in a hydrogel temperature greater than the hydrogel’s LCST.

Heat is generated in the heating elements by joule heating. The amount of power dissipated by the resistive heating element is as shown in Equation 3.2 ($P$ is power in watts, $V$ is voltage, and $I$ is current).

$$P = VI \quad (3.2)$$

$$E = Pt \quad (3.3)$$

$E$ is energy in joules, $P$ is power in watts, and $t$ is time in seconds. Given that watts are equal to joules per second, Equation 3.3 describes how SkinMorph’s electrical subsystem must be able to provide enough power in joules per second for enough seconds that the required energy in joules is dissipated. Recall from Section 2.2 that joule heating outputs energy in the form of heat as opposed to light or vibration, so this energy output is in the form of heat for the hydrogel.

Given that SkinMorph should be fully worn by the user, low power usage results in a variety of benefits towards this goal including a smaller battery, less potential for uncomfortable heating of the skin, and smaller circuit components. However, there is an inherent tradeoff between low power and fast system response. If $E$ in Equation 3.3 is fixed, then a lower power system results in a longer time for activation; for the activation time to be shorter, the power must be increased. The constraints of change in temperature and heat as well as the desire for a low power system with an acceptable speed of response guided the design of SkinMorph to its final parameters. The system is tuned to use as little power as possible while still changing the stiffness of the hydrogel. Specific numbers regarding power, efficiency, heat, and temperature are available in Section 3.8.
3.2.1.3 Voltage versus Resistance

Given a fixed amount of power necessary to operate SkinMorph with a certain response speed as discussed in Section 3.2.1.2, the driving voltage and resistance of the heating elements are related by the in Equation 3.4.

\[ P = \frac{V^2}{R} \]  

(3.4)

The resistances of the nichrome wires embedded as heating elements in the silicone skins vary from 5Ω to 25Ω with most being near 20Ω. This relationship naturally restricts the range of voltages available as operating voltages to the system depending on the watts of power needed to run the system. At 5 VDC the power delivered to the typical 20Ω heating element is described by Equation 3.5.

\[ P = \frac{(5V)^2}{20\Omega} = 1.25W \]  

(3.5)

At this point in the design, the system is constrained such that the hydrogel and silicone skins must be refined to operate successfully with 1.25W of power or less. Examples of refining the system include varying the chemical composition and volume of hydrogel to allow for successful stiffness tuning at 1.25W. Further discussions of the power system are available in Section 3.3.2.1 regarding power system architecture and Section 3.8 regarding efficiency.

3.2.1.4 Electrical Safety

One of the reasons that SkinMorph operates at 5VDC is human safety concern. Wet or broken human skin has a minimum resistance of 1000 Ω, so the worst case current which would travel through the body at 5VDC is 5 mA, an amount which would cause mild sensation but would not be fatal. Care is taken not to place SkinMorph on wet or broken skin, but this scenario was considered out of an abundance of caution.

As a secondary measure to protect both the wearer and the circuit components, the Morphio includes two fuses in case of a short. The first fuse is inline with the input from the battery. This fuse will blow before the battery can heat up due to
excessive current draw if a short occurs. The second fuse is inline with the output to the heating element to prevent excessive current draw due to a short and to prevent overheating of the heating element as discussed in 3.2.2.1.

3.2.2 Wearable Device Considerations

The following section describes the careful specification of insulators, conductors, fabrication methods, and application techniques to ensure the comfort and safety of the user given the on-skin nature of SkinMorph.

3.2.2.1 Heat

The pain threshold of human skin is around 45°C [4]. The silicone skins must heat up to 36°C to tune their stiffness (see Section 4.1.2 for more information). SkinMorph is an open-loop control system; there are no sensors in the silicone skins to confirm that the temperature of the system stays between 36°C and 45°C. Therefore, the system must be inherently designed to minimize the likelihood that the temperature will rise above 45°C and discomfort or burn the wearer.

To avoid hotspots on the underside of the PCB, no components are placed on the bottom of the final revision Morphio board. The only metal exposed on the underside of the board are the through hole connections for the nichrome crimps (see Section 3.3.2.3). The board is mounted to the skin via double sided mounting tape which is 1.6mm thick. This adhesive layer also provides protection for thermal discomfort and electrical connection caused by the crimp connections on the underside of the board.

The Morphio also includes two fuses, partially for heat purposes, as discussed in Section 3.2.1.4.

By design, nichrome wire heats to high temperatures when conducting current. The hydrogel requires a heating element like nichrome wire to alter its stiffness, but the nichrome must not cause irritation to the skin. There are three methods used as appropriate in applications for protecting the skin from the heating element leads that connect the control boards to the silicone skin.
• **Short leads:** When the control board is placed adjacent to the silicone skin, the leads are short and taut enough such that they cannot touch the skin. Figure 3-4 shows an example.

• **Silicone layer:** A layer of silicone can be placed underneath the nichrome traces for protection with the same skin-safe adhesive as the silicone skin.

• **Copper wire crimp:** For long leads, crimping nichrome to copper wire serves two purposes. First, the insulation and low temperature of the copper wire protects the wearer’s skin. Second, the low resistivity of copper allows for more power to be dissipated by the nichrome inside the silicone skins, as opposed to wasting power in the external nichrome leading back to the control board.

![Figure 3-4: An image from an early on-skin system test. The electronics are placed very close to the silicone skin, so the nichrome leads (called out by the red arrow) are very short and cannot touch the wearer's skin.](image)

### 3.2.2.2 Miniaturization

A desired characteristic of the entire SkinMorph system is to be fully and comfortably worn by the wearer, including the PCBs and batteries necessary to tune the stiffness
of the hydrogel. Therefore, the custom PCB is as small as possible while retaining full functionality, staying below thermal requirements, and allowing for rework of surface mount components by hand. Specifically, the minimum part size for easy board rework by hand is 0603 imperial, or 0.060" by 0.030" in length and width.

One example of a design choice for miniaturization is off-boarding all components for writing to the processor over USB. Instead, the circuit board is programmed by connecting an external device directly to its Serial Peripheral Interface (SPI) pins, saving board space that would have been used by the USB to SPI conversion chip.

One constraint of PCB miniaturization is the board space required to dissipate the heat that the voltage conversion and power MOSFET chips output; this heat must be dissipated to keep all components within their rated operating temperature ranges but must not cause the wearer’s skin to heat up uncomfortably as described in 3.2.2.1. Reducing the PCB size increases the difficulty of dissipating this heat as desired. As a result, the final board size is 1" by 1", a size which allows for placement of all components on the top side of the board while not causing the PCB to overheat uncomfortably.

3.2.3 Cost

The lab in which this research was conducted has a history of creating accessible or open source projects available for hobbyists. An initial goal of this research was to design SkinMorph such that it could be released to the public if the final result was accessible with consumer tools and materials. However, the hydrogel formulation requires access to a fume hood, so as of this writing SkinMorph will not be released as a kit or set of instructions.

Due to this desire for accessibility, many of the design choices resulted in using easily sourced materials such as using consumer grade silicone and LiPo batteries. Parts were chosen to keep costs down in the hope that the final product would not be financially prohibitive. Therefore, an emphasis on simplicity and low cost per board influenced the final PCBs. For example, the entire system could have operated at a 10V instead of 5V according to initial calculations. However, surface mount power
supplies which could provide 10V output from a 3.7V nominal LiPo battery were both much more expensive ($8 instead of $1) and much larger in footprint which would have increased the cost of fabrication for each PCB. Table 3.1 shows the result of considering cost as a design constraint. Noticeably, the three peripheral modules have one component each that significantly drives the price.

<table>
<thead>
<tr>
<th>Board</th>
<th>PCB</th>
<th>Parts</th>
<th>Total</th>
<th>Cost Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morphio</td>
<td>$1.00</td>
<td>$12.26</td>
<td>$13.26</td>
<td>ATmega328P ($2.11)</td>
</tr>
<tr>
<td>Programming</td>
<td>$1.00</td>
<td>$7.99</td>
<td>$8.99</td>
<td>SPST Switch ($7.13)</td>
</tr>
<tr>
<td>Bluetooth</td>
<td>$1.00</td>
<td>$20.15</td>
<td>$21.15</td>
<td>Bluetooth Radio (RN-42, $16.19)</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>$1.00</td>
<td>$9.07</td>
<td>$10.07</td>
<td>Accelerometer (ADXL335, $6.62)</td>
</tr>
</tbody>
</table>

Table 3.1: Cost breakdown of the Morphio family of circuit boards.

### 3.3 Morphio Design

Morphio is an Arduino-compatible printed circuit board. Its components can be grouped into four categories: power system, processor and necessary processor peripherals such as clock system, heating element output, and peripheral module connection. Morphio is designed with on-skin mounting and peripheral module attachments in mind.

#### 3.3.1 Device Overview

Morphio’s power subsystem converts incoming power from the LiPo battery between 2.8V and 4.2V to a 5V output with a switching boost converter described in Section 3.3.2.1. The skin output subsystem includes a driving MOSFET, safety fuse, and special output crimps as discussed in Section 3.3.2.3. The processor and external components necessary for the processor to function are covered in 3.3.2.2. The 20-pin connector for mounting the peripheral components is presented in Section 3.3.2.4.

The architecture of Morphio is based on prior work at this lab on DuoSkin [20] which in turn was based on the open source hardware design of SparkFun Electronics Arduino Pro Mini 328 [42].
Figure 3-5: SkinMorph base board schematic.
3.3.2 Design Considerations and Constraints

3.3.2.1 Power System

The Morphio power system is designed to be as efficient as possible while taking up a small footprint. A linear voltage regulator style power system requires fewer components than a switching power system, but linear voltage regulators tend to be less efficient. The tradeoff between footprint and efficiency was made; Morphio has a switching power system. Figure 3.3.2.1 is a Morphio board with the power system outlined. The leftmost black component highlighted is the switching power supply, and the rightmost black component is the surface mount inductor which is necessary for the switching regulator to function. A linear regular would not require the inductor. The inductor takes up 3.6% of the PCB area, although sacrificing that area is worthwhile due to the switching regulator’s maximum 96% efficiency [30]. Comparatively, a linear voltage regulator would have to have an input voltage almost equal to its output voltage to approach 96% efficiency; almost equal input and output voltages are impossible for SkinMorph due to the range of possible input voltages.

![Morphio board with power system outlined](image)

Figure 3-6: A Morphio board with the power system outlined in red.

Power and efficiency calculations are available in Section 3.8. Section 3.2.1 explains the constraints which led to the 5VDC operating voltage.
3.3.2.2 Processor

For ease of programming, Morphio has the same ATmega328P processor as many Arduino-compatible microcontrollers. Choosing the ATmega328P eliminated any uncertainty about the bootloading or programming processes since the chip is compatible with the Arduino integrated developer environment (IDE). Using the Arduino IDE also allows for easy monitoring of serial communication, a common debugging technique. Significant amounts of software-level effort were eliminated by choosing an Arduino-compatible processor.

This processor is an 8-bit AVR microcontroller. It can operate between 1.8V and 5.5V [1], so the 5V operating voltage of SkinMorph is acceptable. At this voltage, any clock speed below 20MHz is within the safe operating range. Earlier revisions of Morphio used lower voltages, such as 2.5V and 3.3V. These voltages constrained the clock speed to lower values, so 8MHz was selected at that time. As the system changed in operating voltages, the 8MHz clock speed was not altered because SkinMorph does not need higher performance. In particular, an 8MHz clock speed allows for programming by an FTDI programmer (explained in Section 3.4.2.2) at 3.3V or at 5V; a higher clock speed would prevent the 3.3V programmer from working with the system.

All compiled programs used in the testing and demonstration of SkinMorph fit well within the memory of the processor, so no off-chip memory was needed.

3.3.2.3 Heating Element Output

The external heating elements are made of 36 AWG and 38 AWG nichrome wire as discussed more in Section 3.7. This material is not compatible with traditional soldering methods, so another technique must be used to attach the nichrome to the control board. This wire gauge is not compatible with most terminal blocks, so mechanically attaching the nichrome temporarily is also not an option. Further research found that nichrome can be riveted or welded to the circuit board that controls it [47]. However, rivets are too permanent for this application. The technique
which solves these problems is using a right angle crimp connector which is attached to the nichrome wire with a specialized crimping tool. The crimps are press-fit into through-hole pads and may be removed by hand with pliers. The specific crimp used is shown in Figure 3-7.

![Right angle Molex connector](image from datasheet of Molex part number 1726770200).

Each heating element output has two leads, so there are connection points for two right angle crimps, marked as P2 in Figure 3-5 and Figure 3-11. The Morphio is 1" by 1", and the peripheral modules are 1" by 5/8"; the right angle connectors snap into the Morphio in a region which is not covered when a peripheral board is mounted.

A power MOSFET (Q1 in Figure 3-5) driven by a pin on the ATmega328P supplies the output power. Output efficiency calculations are available in Section 3.8.

### 3.3.2.4 Peripheral Module Connection

The three peripheral modules are intended to reduce the size of the Morphio without removing functionality. Choosing the connector between the Morphio and the peripheral modules required finding a mechanically and electrically reliable connector with large enough current carrying capacity and small enough form factor. The most thoroughly tested connector which fits the requirements is a 20-pin connector from Hirose Electric’s DF12 series, similar to those used in the stackable TinyCircuits line of Arduino-compatible products [44]. This connector can carry 300mA per pin which is enough for each peripheral module. It is designated as P1 in in Figure 3-5.
3.3.2.5 PCB Layout and Board Size

Morphio prioritizes miniaturization for ease of placing the entire SkinMorph system on the body. The final PCB size is 1" by 1". Figure 3-8 displays the density of traces across the board; there is little room for further miniaturization due to trace density. The only regions without many traces are a ground plane placed underneath the ATmega328P (labeled U1 in Figure 3-5), a region below the potentially noisy power signals running through the JST connector (labeled P3) from the LiPo battery, and a region surrounding the right angle crimp connection points (labeled P2). For noise reasons, these areas do not have many traces, so they are not the low-hanging fruit of removable space that they may seem to be.

![Figure 3-8: Layout of Morphio in 2D view in Altium Designer. Red denotes top layer traces, and blue denotes bottom layer.](image)

This board has three exposed pads for testing and bypassing of the power system, unlabeled but visible above component Q1 in Figure 3-8. The three pads are the signals ground, 5VDC for powering the circuit, and VRAW, the incoming signal from the LiPo battery which varies between 2.8V and 4.2V. Exposure of these signals allows the board to be used with an external power supply that may be able to provide more power than a LiPo battery in testing scenarios when the system is not worn on the body.
While the Morphio is 1" by 1", all three peripheral modules are 1" by 5/8" as seen in Figure 3-9. This is the largest board size for the peripherals such that the peripheral board does not sit outside of Morphio’s boundaries and does not hit the JST connector. The JST connector is a tall component; no smaller JST connector could be used due to the current capacity needed. The JST series contains industry standard battery connectors, hence the choice to use the JST connector despite its height. Figure 3-10 shows that the JST connector would cause the peripheral board to sit askew if the peripheral board extended above the JST connector.
3.3.3 Assembly

Figure 3-11 and Figure 3-12 show an assembled Morphio. These modules were assembled by using a solder mask stencil to apply solder paste, placing the surface mount components by hand, and heating the boards in a reflow oven.

Figure 3-11: Fully-assembled SkinMorph base board, top view.

Figure 3-12: Fully-assembled SkinMorph base board, bottom view.
3.3.4 Test

Each Morphio board undergoes a series of tests to confirm proper operation.

1. **20-pin connector** The 20-pin connector is tested for shorts and discontinuities first because successful connection of the Programming Module is necessary for subsequent tests.

2. **Bypass of power system** The Programming Module is connected and power and ground are provided to the appropriate pins. At this point, the AT-mega328P should have power which can be confirmed with a multimeter.

3. **Bootloading** The Programming Module is used to bootload the Morphio as described in Appendix B. Error messages in the Arduino IDE console during bootloading are used to debug any issues at this step.

4. **Programming and LED test** After bootloading, the Programming Module is used to upload a short program (as described in Appendix C) which toggles the Morphio’s heartbeat LED when the switch on the Programming Module is toggled.

5. **Power system test** At this point, only the power system and heating element output are untested. First, a short program which blinks the Morphio’s heartbeat LED once a second is uploaded. Then, the Programming Module is removed; this step prevents the problematic simultaneous connection of two different power supplies. A LiPo battery of appropriate capacity is attached to the board while an oscilloscope monitors the voltages before and after Morphio’s power conversion chip. Upon confirmation that the boost converter outputs 5VDC, the next test (which tests whether the power system can supply enough current) can be conducted.

6. **Output power resistor test** For consistency in resistance readings and simplicity of attaching instrumentation such as oscilloscope probes, the output
system is tested with a power resistor instead of with a nichrome heating element. Depending on the values of the fuses placed on the Morphio, a resistance which pulls almost the maximum current that the fuse can handle continuously is chosen. The fuses are chosen such that the power chip cannot be harmed. A program is uploaded which turns on the output when the switch is toggled. The FTDI breakout must be removed before applying power from the LiPo battery; otherwise, the system will have two conflicting power supplies. The power resistor is connected, the battery is connected, and the board is observed through oscilloscope readings and a FLIR thermal camera [11].

Assuming the Morphio completes all tests within the expected voltage, power, and thermal operating ranges, the board is ready for use.

### 3.4 Programming Module

The Programming Module offloads Morphio’s bootloading, programming, and testing capabilities to a 1" by 5/8" daughterboard, allowing for board miniaturization and simple on-skin mounting.

#### 3.4.1 Device Overview

The Programming Module has a 4-pin bootloading header (P3 in Figure 3-13), a 6-pin programming header (P1), and a 20-pin male connector (P2) which mates to the 20-pin female connector on a Morphio. Finally, a pullup resistor (R1) and single pole single throw (SPST) switch (S1) complete the board.
3.4.2 Design Considerations and Constraints

3.4.2.1 Bootloading Header

A bootloader is a piece of firmware that runs automatically when a processor receives power. One example of this is the bootloader that loads an operating system on a computer after boot up. In the case of an Arduino-compatible device, an Arduino-compatible bootloader must be programmed to the device to allow it to receive new firmware from the Arduino IDE on a computer. Before bootloading, a blank microcontroller will not know to look for the incoming serial transmission which uploads new programs. Arduinos sold to consumers come with this bootloader already on the processor chip.

Assuming that a bootloader is never overwritten or corrupted, bootloading should only need to happen once per microcontroller. For this reason, offloading the bootloading pads to a peripheral board is an excellent tradeoff for more space on the Morphio. To lower cost, the bootloading header is presented as four exposed pads on the Programming Module, as opposed to including a 4-pin component for attaching wires. Instead, wires are soldered to the pads when bootloading is needed and removed when bootloading is completed, given that bootloading is a one-time operation.

Figure 3-13: SkinMorph Programming Module schematic.
for a microcontroller. The four signals exposed here are the microcontroller’s reset pin and the three serial peripheral interface (SPI) signals referred to as MOSI, MISO, and SCLK. Power and ground must also be connected for this operation to work, although those can be accessed from the programming header and are therefore not repeated in the bootloading header.

See Appendix B for detailed bootloading instructions including appropriate wiring.

### 3.4.2.2 Programming Header

Most Arduino variants are capable of connecting to a Universal Serial Bus (USB) cable in order to communicate to a connected device and to receive power. Some Arduino variants, particularly those designed to be as small as possible, remove the chip which converts transistor-transistor logic (TTL) signals, the type of serial communication generated by the Arduino’s processor, to USB-compatible signals. Removing this chip also allows for the removal of the USB connector which can be one of the larger components on the entire board. Given the miniaturization design constraints of Morphio, the USB components are excluded from the board. Instead, a 6-pin, 0.1” pitch header exposes the power and data signals used for serial communication. These signals would normally be routed to the USB to serial converter chip, but instead a device such as a SparkFun FTDI Basic Breakout, shown in Figure 3-14, can be connected to the 6-pin header [41]. This board is 0.9” by 0.7” to give context for how much board area is saved by using a programming header instead of onboard USB capabilities.

![Sparkfun FTDI Basic Breakout with a quarter for scale](from [41]).
The programming connector resided on the underside of prior Morphio revisions, but the final revision board is designed to have as few pads on the bottom side of the board as possible for ease of placement on the skin.

Figure 3-15 shows the FTDI breakout connected to the Programming Module which itself if connected to a Morphio. In this configuration, the Morphio receives power from the connected USB device, new firmware may be uploaded, and serial communication can be established between the Morphio and the connected device. This serial connection may be used to transmit data in real time about the SkinMorph device.

One important note is that neither the FTDI breakout nor the 20-pin connectors between the Programming Module and the Morphio are capable of delivering the amount of current necessary to drive the stiffness tuning output. Therefore, the FTDI breakout is only used to power the board during new firmware upload and debugging. If wired serial communication is necessary while driving the stiffness tuning output, then the power signal from the FTDI programmer must not be connected to the Programmer Module, and a separate power supply must be connected to the Morphio. Only the common, transmit, and receive signals should be connected in this scenario. See Appendix C for detailed programming instructions.
3.4.2.3 Debugging Switch

A switch is a useful way to control a circuit without having to reprogram it every time that a change should be made. However, even small manual switches are large in comparison to the 1" by 1" size of Morphio, so the final Morphio has no onboard switches; the Programming Module has a switch instead. Often circuit evaluation or debugging of unexpected behavior is conducted while a wired link is established between the circuit and a computer for real time monitoring. Therefore, the switch was placed on the Programming Module to complement the programming header as a debugging tool, as opposed to placing the switch on a separate "Switch Module".

3.4.3 Assembly

Figure 3-16 and Figure 3-17 show an assembled Programming Module, assembled by hand with a reflow oven in the same manner as the Morphio.

Figure 3-16: Fully-assembled SkinMorph Programming Module, top view.

Figure 3-17: Fully-assembled SkinMorph Programming Module, bottom view.
3.4.4 Test

The 20-pin connector was tested by hand to prevent any shorts from damaging the Morphio processor when plugged in. The switch was tested by applying a multimeter across the switch terminals and confirming that the switch connected and disconnected the terminals when flipped. The bootloading header signals were tested to confirm their ordering. The programming header signals were also tested to confirm their ordering; the labels were found to be flipped, although the order of the signals was as intended because the Programming Module did mate correctly with the FTDI programmer. The handwritten labels in Figure 3-17 are due to this error. Successful bootloading and programming of a Morphio with each Programming module confirmed the functionality of the board. Finally, a simple blinking LED program was written and uploaded to confirm that the switch worked; when the switch was flipped, the heartbeat LED on the Morphio toggled.

3.5 Bluetooth Module

The Bluetooth Module provides connectivity to a cell phone or other Bluetooth enabled device to allow for monitoring or interaction with the system as desired by the user. This board is a 1" by 5/8" daughterboard.

3.5.1 Device Overview

The Bluetooth Module consists of a RN-42 Bluetooth component with an integrated antenna plus the voltage conversion circuitry necessary to control it, a 20-pin connector, and some debugging LEDs.
### 3.5.2 Design Considerations and Constraints

The RN-42 Bluetooth component operates at 3.3V, but Morphio runs at 5V. Therefore, a 5V to 3.3V converter is included to power the RN-42. Other circuitry is included to convert the transmit and receive signals from 3.3V to 5V; this circuitry is based on the open source hardware design of SparkFun Electronics Bluetooth Mate Silver [40]. The Bluetooth Mate Silver includes two status LEDs which are included in the Bluetooth Module.

The RN-42 is a Bluetooth device with an on-chip antenna. This component is suitable for SkinMorph because it is low power, small form factor, and surface mount [38]. It is a Class 2 device resulting in a data rate up to 3 Mbps within 20 meters [3] which is more than enough range for SkinMorph’s intended applications. Additionally, choosing the RN-42 means that the Bluetooth Module is very similar to the
SparkFun Bluetooth Mate Silver, making the various SparkFun open source code and documentation available as guides for the designers and users of SkinMorph.

### 3.5.3 Assembly

Figure 3-19 and Figure 3-20 show an assembled Bluetooth Module. These modules were assembled by using a solder mask stencil to apply solder paste, placing the surface mount components by hand, and putting the boards in a reflow oven.

![Fully-assembled SkinMorph Bluetooth Module, top view.](image1)

![Fully-assembled SkinMorph Bluetooth Module, bottom view.](image2)

#### 3.5.4 Test

Basic connectivity tests were conducted to confirm that both 20-pin connectors were seated correctly without shorts. The power system was confirmed to convert voltage to 3.3V correctly.
The Bluetooth RN-42 chip looks like a serial interface to any circuit connected to it. Therefore, testing consisted of setting up a serial monitor program, connecting to the RN-42 chip with a serial connection, and testing the connection and pairing as described in SparkFun’s guide to their RN-42 based board [43]. Successful tests resulted in Bluetooth Modules ready to be deployed in application examples.

3.6 Accelerometer Module

The Accelerometer Module, when paired with the correct firmware, directs the circuit board to activate the hydrogel in response to a certain movement or set of movements. This board is a 1" x 5/8" daughterboard.

3.6.1 Device Overview

The Accelerometer Module has an accelerometer, a voltage converter to power the accelerometer, and two 20-pin headers.

![SkinMorph Accelerometer Module schematic.](image)

Figure 3-21: SkinMorph Accelerometer Module schematic.
3.6.2 Design Considerations and Constraints

Because the accelerometer runs at 3.3V, a 5V to 3.3V converter is included. Due to the large amount of space available on the 1" by 5/8" peripheral PCB after placement of the accelerometer chip, there is a 20-pin male connector on the bottom and a 20-pin female connector on the top. This arrangement allows the accelerometer and another board to be plugged into a Morphio at the same time. In this manner, a wireless Bluetooth connected device or a wired FTDI breakout could transmit accelerometer readings to a user in real time to expose which movement caused Morphio to activate the heating element output.

The accelerometer used is an Analog Devices ADXL335, a chip commonly used in Arduino-compatible accelerometer boards such as the Adafruit triple-axis accelerometer. Using a similar chip to this readily available board follows the design constraint of keeping cost down and the system hobbyist-accessible.

3.6.3 Assembly

Figure 3-22 and Figure 3-23 show an assembled Accelerometer Module. These modules were assembled by using a solder mask stencil to apply solder paste, placing the surface mount components by hand, and putting the boards in a reflow oven.

Figure 3-22: Fully-assembled SkinMorph Accelerometer Module, top view.
3.6.4 Test

Basic connectivity tests were conducted to confirm that both 20-pin connectors were seated correctly without shorts. The power system was confirmed to convert voltage to 3.3V correctly.

A test program was written to read accelerometer data and transmit it back over serial communication to a serial monitor. The program confirmed the functionality of the device. Figure 3-24 displays the Accelerometer Module connected to a Morphio and a Bluetooth Module during test. A serial connection to a computer allows for the accelerometer data to be monitored as shown in Figure 3-25.

Figure 3-24: An Accelerometer Module in between a Morphio and a Bluetooth Module during testing.
Successful testing means that the Accelerometer Module can provide a triggering mechanism for the system. For example, one application could be programmed such that if the measurement of each axis of acceleration changes more than 50% in a second, then the system should automatically increase the stiffness of the material. Then, if the accelerometer readings stay moderately stable for 20 seconds, the material should decrease in stiffness.

### 3.7 Joule Heating Trace Design

This section describes the electrical design of the nichrome heating elements. The process of fabricating the nichrome traces to be embedded in the silicone skins is described in Section 5.1.

#### 3.7.1 Device Overview

The nichrome traces serve as the heating element within the silicone skin. Current flows through the traces as desired to cause stiffness changes in the hydrogel encaps-
sulated by the silicone skin. Figure 3-26 shows a silicone skin with nichrome traces embedded. The nichrome leads exiting the skin are visible in the bottom right of the image.

![Figure 3-26: A large arrow-shaped silicone skin with embedded nichrome traces and without hydrogel. The entry and exit leads are visible in the bottom right corner.](image)

### 3.7.2 Design Considerations and Constraints

#### 3.7.2.1 Nichrome Material Choice

Nichrome 80 wire is the choice for heating element as justified in Section 2.2.1. The gauges of nichrome wire which work successfully with the circuit board design and the mechanical fabrication method are 36 AWG and 38 AWG. Measurements of the nichrome 80 wire used indicated that 36 AWG nichrome 80 has a resistance per foot of 27.2Ω/ft and 38 AWG nichrome 80 has a resistance per foot of 43.1Ω/ft. These values are important for the calculations involved in the electrical design of the nichrome traces.

Another nichrome constraint is the high resistivity of nichrome wire, even though this high resistivity satisfies some system requirements. Even short runs of nichrome wire outside of the silicone skins (which therefore do not contribute to the heating of the hydrogel) cause large losses in efficiency. For example, if the control board is placed one inch from the silicone skin and the skin has a six inch internal nichrome trace (an acceptable length as described in Section 3.7.2.2), then two out of eight inches of this nichrome trace are outside of the silicone skins. This ratio results in a
25% loss of power across the nichrome trace even though the outside leads are only an inch long each. This potential efficiency loss results in a nichrome trace design where the two leads of the trace exit the silicone skin as close together as possible to minimize external trace length.

### 3.7.2.2 Acceptable Resistance Range

The minimum trace resistance is a hard limit which must be met to ensure the functionality of the circuit board. This value has to do with the maximum amount of instantaneous current the system can source to the traces which depends on the fuse connected to the heating element output. For example, if the fuse is an 800mA fuse (which is a value that the power supply system and battery of Morphio can safely handle), then the minimum resistance is calculated as follows where the \( \rho \)'s are the resistivities in Ohms per foot of nichrome 80 for 36 AWG and 38 AWG.

\[
I = \frac{V}{R} \tag{3.6}
\]

\[
800mA \geq \frac{5V}{R_{TRACE}} \tag{3.7}
\]

\[
R_{TRACE} \geq 6.25\Omega \tag{3.8}
\]

\[
R_{36AWG} = \rho_{36AWG}(\Omega/ft) * L_{36AWG}(ft) \tag{3.9}
\]

\[
L_{36AWG} \geq 2.75in \tag{3.10}
\]

\[
R_{38AWG} = \rho_{38AWG}(\Omega/ft) * L_{38AWG}(ft) \tag{3.11}
\]

\[
L_{38AWG} \geq 1.75in \tag{3.12}
\]

The maximum trace resistance is a soft limit due to the power requirements of the hydrogel; exceeding the limit will not harm the device, but it will slow down the rate of stiffness change to an undesirable speed. Assuming that for a particular silicone skin and volume of hydrogel 1W of power is needed to alter the stiffness at a minimally acceptable rate, the maximum trace resistance is calculated as follows.
\begin{align*}
P &= \frac{V^2}{R} \\
1W &\leq \frac{(5V)^2}{R_{\text{TRACE}}} \\
R_{\text{TRACE}} &\leq 25\Omega \\
R_{36\text{AWG}} &= \rho_{36\text{AWG}}(\Omega/ft) \ast L_{36\text{AWG}}(ft) \\
L_{36\text{AWG}} &\leq 11.0\text{in} \\
R_{38\text{AWG}} &= \rho_{38\text{AWG}}(\Omega/ft) \ast L_{38\text{AWG}}(ft) \\
L_{38\text{AWG}} &\leq 7.0\text{in}
\end{align*}

Depending on the shape of the silicone skin, different applications use 36 AWG or 38 AWG to satisfy the resistance requirements. For example, a silicone skin requiring 10 inches of nichrome wire to evenly cover the entire volume of hydrogel is forced to use the 36 AWG wire.

3.7.3 Assembly

The process of fabricating the nichrome traces to be embedded in the silicone skins is described with the rest of the silicone skin mechanical instructions in Section 5.1.

3.7.4 Test

Testing the nichrome traces is straightforward. First, a visual inspection confirms that the nichrome trace is physically arranged such that it will have even coverage throughout the silicone skin to reduce the probability of uneven hydrogel stiffening. Next, a multimeter is used for a conductivity test to confirm that there are no breaks in the nichrome wire. Then, a resistance measurement is taken between two points half an inch each from the two locations at which the nichrome wire is expected to exit the silicone skin for which it is designed. If this resistance measurement is within the allowed range for that silicone skin design, then the trace is ready to be embedded within the silicone skin.
3.8 Electrical System Evaluation

This section outlines the calculations performed while designing the electrical system as well as the tests executed to confirm the expected circuit functionality.

3.8.1 Power System Efficiency

The switching regulator on the Morphio varies in efficiency depending on the output current. Figure 3-27 displays the efficiency when $V_{OUT} = 5V$. Since the nominal voltage of a LiPo battery is 3.7V, the solid line indicating $V_{IN} = 3.6V$ should be analyzed. Since Morphio’s operating current varies between 40mA and 1A depending on whether the heating element is on or off, the power system efficiency varies between 85% and 95%. Load testing of the Morphio near the maximum current draw confirmed a functional power system.

![Figure 3-27: A graph of efficiency versus $I_{OUT}$ from [30].](image)

3.8.2 Heating Element Output Efficiency

The power MOSFET used on the Morphio to drive the nichrome heating element is designed specifically to minimize its drain to source resistance ($R_{DS,ON}$) when on. At the maximum operating current of 800mA for the heating element (as determined
by the fuse placed at the output) and a gate to source voltage ($V_{GS}$) of 4.5V, the MOSFET has $R_{DS,ON} = 58 \text{ m} \Omega$ [6]. According to Figure 3 in [6], the Morphio’s $V_{GS}$ equal to 5V will result in an even lower $R_{DS,ON}$. A lower operating current due to a more resistive trace also results in a lower $R_{DS,ON}$. For a conservative efficiency estimate, 58 mΩ is used in calculations here.

Assuming a nichrome trace of 20Ω resistance and ignoring $R_{DS,ON}$, the nichrome trace receives $P = (5V)^2/20 \Omega = 1.25W$ of power. Including the $R_{DS,ON}$ results in fewer than 5V across the nichrome heating element as the MOSFET’s resistance acts as a voltage divider. The actual voltage across the nichrome heating element is $5V \times (20\Omega/20.058\Omega) = 4.986V$. This results in a power output of $P = (4.986V)^2/20\Omega = 1.243W$ which translates to 99.4% efficiency. This efficiency is acceptable for SkinMorph’s application, especially given that most application nichrome traces have resistance around 20Ω.

Measurements of the voltages across the nichrome traces and the driving MOSFET during operation confirmed the low $R_{DS,ON}$ and the high efficiency of the output drive.
Chapter 4

Material Design

This chapter explains the chemical composition of hydrogel and gives quantitative data and evaluation for ten experimental formulations. It also discusses any material choices not covered elsewhere in this thesis.

4.1 Hydrogel Design

4.1.1 Hydrogel Composition

Hydrogel is composed of five chemicals plus water. Each chemical has a different effect on the composition of the hydrogel as explained below.

- **N-isopropylacrylamide (NIPAM)**: Forms the basis of the polymer network during polymerization to create complex branches of long poly(NIPAM) chains

- **Acrylamide**: A monomer which changes the hydrogel’s activation temperature

- **N,N’-Methylene-bis-acrylamide (MBA)**: A cross-linker to allow polymer chains to form 3D networks; more MBA means higher network constraints, higher stiffness when inactive, and less relative change in stiffness when heated

- **Ammonium persulfate (APS)**: Initiates the polymerization process

- **Tetramethylethylenediamine (TEMED)**: Acts as an accelerator to the polymerization process
4.1.2 Hydrogel Experimentation

SkinMorph requires hydrogel which meets certain tactile and thermal specifications. Due to the lack of an existing hydrogel formulation which meets these specifications, experimentation with the hydrogel’s chemical composition was necessary.

The protocol from Geltouch [31] produces hydrogel which is not viscous enough at rest for SkinMorph’s applications. For SkinMorph, the quantities of MBA and APS were varied experimentally until a hydrogel of appropriate viscosity was formed.

Another hydrogel characteristic requiring experimentation is the lower critical solution temperature (LCST). The LCST is the temperature below which all components of a mixture are miscible; above the LCST, the hydrogel stiffens, becomes opaque, and pushes water out from the polymer network. Figure 4-1 shows a hydrogel sample below and above its LCST. Geltouch’s protocol creates hydrogel with LCST around 32°C which is too close to typical human skin temperature at 32°C [24]. An LCST near skin temperature would cause SkinMorph to activate upon mounting the device on the skin, so the control circuitry would not be driving the stiffness change. The LCST was increased above skin temperature by adding extra acrylamide to the solution as posed by Jain et al. [16].

![Image 1](image1.jpg)  ![Image 2](image2.jpg)

Figure 4-1: On the left, a square silicone skin with translucent hydrogel below its LCST. On the right, a square silicone skin with activated hydrogel above its LCST; the activated hydrogel’s polymer network pushes out water which is visible.

To resolve the viscosity and skin temperature issues, ten hydrogel batches were synthesized to tune the viscoelastic properties and LCST. These ten batches differed
in the ratios of the five chemicals in hydrogel other than water as described in Section 4.1.1. First, the amounts of APS and MBA were varied to find an appropriately viscous solution. An intermediary formulation with altered APS and MBA values was created. Next, acrylamide was added to the intermediate formulation in different percentages by mass until the desired LCST was attained. Table 4.1 lists the chemical compositions of each of the ten experimental batches of hydrogel.

<table>
<thead>
<tr>
<th>Batch</th>
<th>NIPAM</th>
<th>Acryl.</th>
<th>MBA</th>
<th>APS</th>
<th>TEMED</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2g</td>
<td>0g</td>
<td>2mg</td>
<td>50mg</td>
<td>150µL</td>
<td>Geltouch formulation</td>
</tr>
<tr>
<td>B</td>
<td>2g</td>
<td>0g</td>
<td>20mg</td>
<td>50mg</td>
<td>150µL</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>2g</td>
<td>0g</td>
<td>2mg</td>
<td>500mg</td>
<td>150µL</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>2g</td>
<td>0g</td>
<td>2mg</td>
<td>1g</td>
<td>150µL</td>
<td>APS value locked here</td>
</tr>
<tr>
<td>E</td>
<td>2g</td>
<td>0g</td>
<td>4mg</td>
<td>500mg</td>
<td>150µL</td>
<td>-</td>
</tr>
<tr>
<td>F</td>
<td>2g</td>
<td>0g</td>
<td>8mg</td>
<td>500mg</td>
<td>150µL</td>
<td>-</td>
</tr>
<tr>
<td>G</td>
<td>2g</td>
<td>0g</td>
<td>12mg</td>
<td>500mg</td>
<td>150µL</td>
<td>-</td>
</tr>
<tr>
<td>H</td>
<td>2g</td>
<td>0g</td>
<td>6mg</td>
<td>500mg</td>
<td>150µL</td>
<td>MBA value locked here</td>
</tr>
<tr>
<td>I</td>
<td>1.98g</td>
<td>0.02g</td>
<td>6mg</td>
<td>500mg</td>
<td>150µL</td>
<td>1% acrylamide by mass</td>
</tr>
<tr>
<td>J</td>
<td>1.88g</td>
<td>0.12g</td>
<td>6mg</td>
<td>500mg</td>
<td>150µL</td>
<td>6% acrylamide by mass</td>
</tr>
</tbody>
</table>

Table 4.1: Chemical composition and notes regarding the ten experimental hydrogel formulations. Batch A is the formulation from Geltouch [31] and Batch J is the final SkinMorph formulation.

Adding APS decreases the average polymer chain length which makes the hydrogel feel more sticky due to the polymer flowing more easily when inactive. Adding MBA causes the solution to be more viscous at rest due to more cross-links in the polymer network. Adding acrylamide increases the LCST. The samples were compared to find a composition that matches the change in stiffness, speed of temperature increase and decrease, and LCST desired for SkinMorph. Specific values and images for the tuned hydrogel characteristics are available in Section 4.1.3.

The altered hydrogel synthesis instructions below are based on the protocol posed by Miruchna et al. [31] which itself is based on Wang et al.’s original protocol [46]. The quantities in the instructions are altered to match SkinMorph’s final chemical composition chosen as a result of the tuning process. This protocol creates about 25mL of hydrogel. All silicone skins created for SkinMorph require 5mL or less of hydrogel each, so batches of 25mL were divided between multiple skins.
1. Dissolve N-isopropylacrylamide (1.88mg) in deionized water (20mL)

2. Add acrylamide (0.12mg) to the solution and dissolve it (with a vortex mixer)

3. Add N,N’-Methylene-bis-acrylamide (6mg) to the solution and dissolve it

4. Put the solution on ice for 10 minutes

5. Dissolve APS (500mg) in deionized water (3mL)

6. Pour the N-isopropylacrylamide / N,N’-methylene-bis-acrylamide solution in the synthesis container (in SkinMorph’s case, the container is the silicone skin)

7. Add TEMED (150uL) to the container

8. Add APS solution (1500uL) to the container

9. Refrigerate the container at 4 °C for eight hours

### 4.1.3 Hydrogel Evaluation

This section contains data and evaluation from the hydrogel experiments, especially for the finalized hydrogel formulation.

Figure 4-2: From left to right, the top row shows batches A, B, C, D, and E while not activated. From left to right, the bottom row shows batches F, G, H, I, and J while not activated.
Figure 4-2 displays all ten batches while not activated. Figure 4-3 displays all ten batches while activated. While the formulations look similar in their transparent and activated states, the viscosity of each sample varies significantly.

![Figure 4-3: From left to right, the top row shows batches A, B, C, D, and E while activated. From left to right, the bottom row shows batches F, G, H, I, and J while activated.](image)

Table 4.2 shows the LCST of each batch of hydrogel. The LCST was measured for each sample by synthesizing 2mL of hydrogel in a small test tube, submerging the tube in water, and measuring the temperature of the water at the time of activation. Adding acrylamide to batches I and J did increase the LCST from that of batch H as expected.

<table>
<thead>
<tr>
<th>Batch</th>
<th>LCST (°C)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>34</td>
<td>Geltouch formulation</td>
</tr>
<tr>
<td>B</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>28</td>
<td>-</td>
</tr>
<tr>
<td>E</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>F</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>G</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>H</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>I</td>
<td>31</td>
<td>1% acrylamide by mass</td>
</tr>
<tr>
<td>J</td>
<td>36</td>
<td>6% acrylamide by mass</td>
</tr>
</tbody>
</table>

Table 4.2: Hydrogel LCST of each batch. Batch J is the final SkinMorph formulation due to its LCST of 36 °C.
Table 4.3 gives data regarding the behavior of each batch when heated. As seen in Figures 4-2 and 4-3, all ten batches were placed into identical square silicone skins rather than one of the more complex application shapes. A simple, uniform shape was chosen to ensure consistency of data. These square skins measure 1" by 1" by 4mm, the same depth as the application silicone skins. A heating element with 2.5W output was placed beneath each silicone skin. The three data points recorded were the time from applying heat to seeing a change, the time from applying heat to a full change in stiffness, and the time from removal of heat to completely deactivated, transparent gel.

<table>
<thead>
<tr>
<th>Batch</th>
<th>Time to visible change</th>
<th>Time to full change</th>
<th>Cooling time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0:07</td>
<td>0:53</td>
<td>4:52</td>
</tr>
<tr>
<td>B</td>
<td>0:08</td>
<td>1:42</td>
<td>14:20</td>
</tr>
<tr>
<td>C</td>
<td>0:08</td>
<td>1:10</td>
<td>6:48</td>
</tr>
<tr>
<td>D</td>
<td>0:06</td>
<td>1:03</td>
<td>8:08</td>
</tr>
<tr>
<td>E</td>
<td>0:05</td>
<td>1:49</td>
<td>9:26</td>
</tr>
<tr>
<td>F</td>
<td>0:11</td>
<td>1:14</td>
<td>6:34</td>
</tr>
<tr>
<td>G</td>
<td>0:05</td>
<td>0:48</td>
<td>16:41</td>
</tr>
<tr>
<td>H</td>
<td>0:06</td>
<td>1:23</td>
<td>16:05</td>
</tr>
<tr>
<td>I</td>
<td>0:06</td>
<td>0:58</td>
<td>10:47</td>
</tr>
<tr>
<td>J</td>
<td>0:05</td>
<td>1:15</td>
<td>5:27</td>
</tr>
</tbody>
</table>

Table 4.3: Data from a test recording the activation and deactivation times of each batch of hydrogel when heat is applied. All times are listed in minutes:seconds. The batches are labeled in correspondence to Table 4.1.

Batch J was chosen based on its LCST and its viscosity, but its speed of stiffening was also important. Its activation time of 1 minute and 15 seconds and cooling time of 5 minutes and 27 seconds are acceptable for SkinMorph, so further experimentation was not necessary.

4.2 Miscellaneous Material Selection

This section briefly justifies the material choices not covered elsewhere in this thesis.
4.2.1 Silicone Skins

Tests were conducted with latex, silicone, molding wax, and other materials to determine which material to use to encapsulate the hydrogel. Silicone is skin safe, transparent, flexible, and non-reactive with hydrogel, making it suitable for SkinMorph. The specific silicone used is SORTA-Clear 37, a soft and transparent two part mix silicone.

4.2.2 Dissolvable Thread and Fabric

An intermediate step of the mechanical workflow described in Section 5.1.1 requires dissolvable thread and fabric. A high-thickness dissolvable fabric was used, as the medium and thin versions would not hold the nichrome wire in place without tearing. Sturdy dissolvable thread was used because thin thread could not control nichrome wires even as thin as 38 AWG. The sewing technique relies on work from Rahimi et al. [37].

4.2.3 Skin Adhesive

Telesis Silicone Adhesive is an adhesive used for special effects makeup. It is specifically designed to adhere silicone to the skin very reliably. A separate removal solution must be used to remove the adhesive due to its strength. Since the adhesive and removal solution are designed for special effects makeup and other human skin-specific use cases, these materials are skin safe and suitable for SkinMorph.
Chapter 5

Mechanical Design

This chapter covers the design process and challenges for the mechanical subsystem of SkinMorph. This chapter, in combination with Section 4.1.2 which explains the hydrogel synthesis and Chapter 3 which details the electrical design and implementation, should allow full replication of the project. This chapter also provides instructions for operation of a complete SkinMorph system.

5.1 Mechanical Workflow and System Operation

This section describes the specific steps to create and operate a SkinMorph device.

5.1.1 Creating a Finished Silicone Skin Overlay

This section describes the specific steps required to create a silicone skin which is ready to be connected to a circuit board.

1. CAD
   
   (a) Design an injection mold with CAD software. An example of a mold designed in Solidworks is shown in Figure 5-1.
   
   (b) Output the design to a 3D printer-friendly file format. Be sure to keep the internal mold surfaces free of 3D printing support structures; the imperfec-
tions left when removing the supports decrease the quality of the silicone skins.

Figure 5-1: A rendering of an arrow-shaped injection mold designed in Solidworks. The rectangular brackets are for ease of separation when releasing the silicone skin from the mold. The funnel on the top piece is where the silicone is injected.

2. **3D printing**

   (a) Print the molds. SkinMorph used a Formlabs Form 2, a printer with SLA technology. An example mold is shown in Figure 5-2.

   (b) Cure the molds as specified by the 3D printing method.

3. **Nichrome trace fabrication**

   (a) The sew-and-transfer method described in this section is adopted from the work of Rahimi et al [37].

   (b) Use a sewing machine to sew the nichrome traces. Set up the sewing machine by winding 36 AWG or 38 AWG nichrome wire on the bobbin and inserting it into the machine. Thread the machine with water-soluble thread.
Figure 5-2: A 3D printed mold which creates an arrow-shaped skin overlay when filled with silicone. The two pieces fit together, and silicone is injected through the large opening in the piece on the bottom.

(c) Sew the nichrome trace into a sturdy piece of water-soluble fabric. Sew the trace such that all of the hydrogel within the corresponding silicone skin will be near a nichrome trace.

(d) Test the nichrome trace as described in Section 3.7.4 before proceeding to the next step. At this stage, the part should look like Figure 5-3.

Figure 5-3: A piece of dissolvable fabric embedded with a nichrome trace and dissolvable thread. This trace is intended for a bone-shaped silicone skin overlay. The traces exit the fabric in the bottom right; the traces will exit the silicone skin in the respective location.

4. **Injection molding**

(a) Attach the dissolvable fabric with nichrome trace to the inside of the mold with glue. Close the mold such that the extra nichrome will exit the silicone
skin at the desired location.

(b) Prepare silicone for injection. SkinMorph used SORTA-Clear 37 two part silicone mix.

(c) Inject the silicone into the mold with a large syringe. The silicone should spill out of the mold as shown in Figure 5-4; the extra silicone increases the chance of a mold without bubbles.

(d) Use a vacuum to remove bubbles from the silicone.

(e) While there is mixed silicone, create thin sheets of silicone to be used for sealing the skins later. Pour silicone between two smooth plastic sheets. Then, press the sheets together to ensure a uniformly thin layer of silicone once cured.

Figure 5-4: A mold with cured silicone. Extra silicone has been allowed to leak out of the mold and is visible. The nichrome traces can be seen exiting the mold on the bottom left.

5. Preparation for hydrogel

(a) After 12 hours, open the molds by hand. The silicone will stick to one side of the mold as seen in Figure 5-5. Trim the silicone sticking out of the mold before opening it by hand.

(b) Carefully peel the skin out of the mold.
(c) Trim the excess silicone from the skin with a small pair of scissors, still leaving enough room on the edge to seal the skin later.

(d) Dissolve the exposed dissolvable thread and fabric in a bath of water.

(e) Inspect the skin for imperfections. Small gaps can be sealed with the addition of more silicone.

Figure 5-5: Half of an opened mold with a cured silicone skin still inside of it. The nichrome traces can be seen exiting the skin on the bottom left. The excess silicone around the edges has not yet been trimmed.

6. **Hydrogel synthesis**

(a) Measure the volume of the silicone skin.

(b) Synthesize hydrogel as described in Section 4.1.2. Use the finished silicone skin as the "synthesis container" mentioned in the hydrogel instructions. Fill the skin with the desired volume of hydrogel by calculating a smaller batch with the correct chemical ratios (the instructions given create 25mL of hydrogel which is 5 to 10 skins worth of hydrogel).

7. **Silicone sealing**

(a) Mix silicone to be used like glue to attach a backing to the silicone skin.

(b) Retrieve a thin layer of silicone already prepared and cured. Cut it to the approximate size of the silicone skin to be sealed. Use a small amount of
fresh silicone around the lip of the silicone skin to adhere the thin layer of silicone. Make sure not to trap air bubbles inside the skin when sealing.

(c) After 12 hours, check the seal of the silicone skin. If there are leaks, seal them with more fresh silicone.

(d) Once there are no leaks, trim the excess silicone from the silicone skin such that it is presentable and ready for placement on the body. The silicone skin overlay should look similar to the one in Figure 5-6.

![Figure 5-6: An bone-shaped silicone skin overlay with right angle crimps attached to the nichrome traces. This skin has been sealed and has had any extra silicone trimmed.](image)

8. Trace preparation for PCB connection

(a) Prepare the nichrome traces for connection to the PCB, depending on which of the three nichrome trace methods is used.

(b) **Method 1, bare nichrome**: If the traces between the silicone skin overlay and the control board are short, crimp right-angle connectors onto the nichrome wire to allow for direct connection to the PCB. This may require doubling the nichrome back on itself if the crimps are not rated for such a small gauge.

(c) **Method 2, silicone protection layer**: If the traces are medium length, then a layer of silicone will be laid underneath the traces to protect the skin from contact. Crimp right-angle connectors onto the nichrome wire
to allow for direct connection to the PCB. This may require doubling the nichrome back on itself if the crimps are not rated for such a small gauge.

(d) **Method 3, copper wire**: If the traces will be long, copper wire should replace the exposed nichrome to increase the power efficiency of the system. The copper wire should be crimped to the nichrome as close to the silicone skin as possible. Then, the other end of the copper wire should be crimped with right-angle connectors for connection to the PCB.

(e) **Doubled-up silicone skins**: Some applications may have two silicone skins which share a control board, provided the board has enough capacity to power both skins. These skins should be connected by crimping their nichrome traces (or copper wire) together without causing any shorts.

(f) At this point, the silicone skin is ready to be connected to a Morphio control board.

![Image](image.png)

**Figure 5-7**: A silicone skin with crimped nichrome traces attached to a Morphio. The right angle crimps have been inserted into their connection points. The Morphio has activated the skin overlay, therefore tuning the stiffness of the hydrogel and rendering it opaque.

### 5.1.2 Mounting SkinMorph

This section describes the specific steps required to take a finished silicone skin overlay, attach it to a user, and control it.
1. **Nichrome attachment to PCB**

   (a) Press-fit the right angle connectors crimped to the nichrome traces into the through-hole connection points on the Morphio board.

   (b) If desired, solder the bottom of the connectors to the Morphio, although this step should not be necessary. In the case of intermittent connection, solder should be applied even though it will increase the difficulty of switching silicone skin overlays to that board later.

2. **Silicone skin overlay attachment to user**

   (a) Apply skin-friendly adhesive to the underside of the silicone skin and to the skin of the user.

   (b) Hold the silicone skin overlay in place until the adhesive glue has dried.

   (c) If there is exposed nichrome wire outside of the silicone skin which could make contact with the wearer, place a layer of silicone underneath where the traces will lead to the control board. Secure this layer of silicone with the same adhesive as before. Short nichrome leads and insulated copper wire do not need this layer of silicone.

3. **Electronics mounting to user**

   (a) Finalize the location of the Morphio. The placement of the PCB should prevent any shorting of the nichrome wire, especially when two silicone skins share one control board. It should also ensure that all nichrome wire is blocked from direct contact with the skin.

   (b) Use a thick piece of non-conductive, double-sided, skin-friendly adhesive to place the Morphio on the skin.

   (c) Place the LiPo battery on the skin without plugging it in such that it can be connected to the Morphio. Use the same mounting adhesive as the previous step. If desired, a thinner mounting tape may be used since the battery does not output heat to the same extent as the control board.
4. SkinMorph Operation

(a) Connect the battery to the Morphio.

(b) Observe the system behavior upon power up to confirm that no shorts are present. Immediately unplug the battery if any issues are apparent.

(c) Connect to the Morphio over Bluetooth if the Bluetooth Module is attached.

At this point, SkinMorph can be used as intended. If the accelerometer module is attached, the stiffness should change upon a large change in movement. If the Bluetooth module is attached, the stiffness can be controller with the wearer’s phone.

5.1.3 Removing SkinMorph

This section describes the steps which should be taken to remove SkinMorph safely from a user.

1. Turn off electronics

(a) First, unplug the battery so that it is safe to touch the exposed nichrome traces.

(b) Wait for 30 seconds to ensure the nichrome wire has cooled to room temperature.

(c) Remove the battery from the skin.

2. Remove silicone skin overlay and electronics

(a) Apply the adhesive removal solution. Carefully peel the silicone skin overlay off while continuing to apply adhesive removal solution to the newly exposed skin area.

(b) Remove the Morphio from the skin.

(c) Disconnect the nichrome traces from the Morphio if the board is needed for another skin overlay.
5.2 Mechanical Challenges

SkinMorph has two primary challenges due to its mechanical design and workflow. The first is difficulties in fabrication by hand, and the second is speed of iteration.

Although some parts of SkinMorph’s mechanical workflow are automated, such as the 3D printing stage, there are steps which are unavoidably executed by a human instead of a machine. Fabricating parts by hand for a complex system introduces sources of error and variance. For example, removal of the silicone skin overlays from their 3D printed molds by hand can cause tearing which goes undetected until the skin, full of hydrogel, begins to leak. Refining the mechanical fabrication process to increase the successful production rate of finished silicone skins was a difficult challenge solved only by incremental alterations to the fabrication techniques and material choice.

Many of the steps in the mechanical workflow require hours of waiting; this schedule results in a minimum of four days between creating a new mold shape and determining what changes need to be made to it based on testing with the entire system (namely, with hydrogel and a control board). This speed of iteration puts a limit on the number of application shapes which can be explored in a given amount of time. Additionally, an error, however small, in the process takes at least four days to reconcile if it is not caught before system testing.
Chapter 6

Applications

This chapter documents the example applications explored for SkinMorph. These examples include one for the heel, one for the elbow, one for the wrist, and one focused on aesthetics.

6.1 Heel

A common location on the body in which the toughness of the skin fails to protect from harm is the heel. Shoes, whether ill-fitting or worn for too long, can cause uncomfortable blisters on the heel. This SkinMorph application provides a protective barrier with tunable stiffness for protection from irritating friction. Figure 6-1 shows a heel application.

![Figure 6-1: An application of SkinMorph for the heel. The silicone skin overlay sits against the part of the heel commonly irritated by shoes.](image)
The heel application consists of one silicone skin overlay, one Morphio, and one battery. The Morphio and battery are placed around the ankle, away from the heel due to the movement of the ankle joint. The wires as seen in the rightmost image of Figure 6-1 lead to the Morphio which would be placed on the inside of the ankle with a battery. The leads from the silicone skin overlay to the Morphio are long, so copper wire with crimps adjacent to the silicone skin are used for efficiency of the electronics and to protect the user’s skin from heat.

6.2 Elbow

The elbow example for SkinMorph displays a protective use case in which the system is context-aware. An Accelerometer Module attached to a Morphio alerts the system to a change in user activity. When a user starts a potentially physically dangerous activity, the stiffness of the system is increased to protect in the case of a fall. Figure 6-2 shows the arrow-shaped silicone skin overlays for protection. The arrow design allows for customization of the specific location of the skin overlays. A similar design could be used on the knee joint for related use cases.

Figure 6-2: An application of SkinMorph for the elbow. The rightmost image shows activated hydrogel.

The elbow application can consist of two or four silicone skin overlays. Each pair of arrows requires one Morphio and one battery. If there are two overlays, they can be placed as a pair on one side of the elbow or as mirrored arrows on each side of the elbow. If there are four overlays, one pair of arrows is placed above the elbow, and
one pair is placed below the elbow symmetrically with the first pair. The electronic components are placed on the inside of the upper and lower arm respectively to the upper and lower pairs.

6.3 Wrist

The wrist application is meant to serve as a protection against carpal tunnel. The stiffness of activated hydrogel around a wrist with poor posture reminds the user to type with correct form. The wrist application consists of two silicone skin overlays, one Morphio, and one battery as seen in Figure 6-3.

![Figure 6-3: An application of SkinMorph for the wrist. The image on the right shows the placement of the Morphio and the battery used by both silicone skin overlays.](image)

The wrist application combines interesting aesthetics with useful input to the user. Previous work in restricting movement with novel on-body technology by Oxman et al. inspired the carpal tunnel use case [34].

6.4 Aesthetics

Some applications of SkinMorph are focused on aesthetics and personal expression. One of the earliest versions of SkinMorph focused on a silicone skin overlay to be worn on the face as seen in Figure 6-4.

Customized applications of SkinMorph would allow the wearer to alter the appearance of their body or skin in real time with electronic control. New devices such
as SkinMorph provide unconventional forms of personal expression and identity which are absent from current wearable technology [19].

Figure 6-4: An application of SkinMorph focused on aesthetics. The hydrogel in the silicone skin overlay is activated and opaque. The two wires from the left side of the silicone lead to a Morphio hidden on the back of the neck.
Chapter 7

Discussion and Future Work

This chapter concludes the thesis and discusses limitations and future work.

7.1 Limitations

One significant limitation of SkinMorph is the size of the battery necessary to power the system. Finding a cheap battery which also fit the desired form factor and provided the minimum necessary amount of power resulted in batteries which are not small enough to go unnoticed on the skin. This project was not a battery technology project, so no progress was made towards finding a solution to the battery limitations. Care was taken to use as little power as possible to minimize the battery size, but the inherent constraints of the system resulted in an awkwardly large power source. One potential solution would be using a lower volume of hydrogel which would require less power per silicone skin overlay. However, qualitative testing suggested that the 4mm depth used in the applications was preferred from a tactile perspective.

The structural integrity of the silicone skin overlays varies significantly with each batch, despite improved fabrication techniques. Each step of the mechanical workflow has the potential to add error, and a redesign of a significant portion of the system would be necessary to shorten the steps required. For example, using a professional service to injection mold the skins could increase the success percentage of the skins and strengthen the entire mechanical system, but the cost increase would be dramatic.
The fabrication issues due to the large variance in structural stability of the silicone conflict with the desire for SkinMorph’s applications to include physical protection through skin stiffness tuning. Silicone skins with any defects can be ruptured with less force than it would take to injure the underlying human skin, resulting in a device which does not afford any real protection. A ruggedized fabrication process would allow for SkinMorph to better fit its claims of tunable stiffness for skin protection such as in the case of the elbow application example.

SkinMorph uses open-loop control, meaning that there are no sensors monitoring the temperature of the hydrogel. Therefore, the hydrogel can heat up past its LCST (care was taken not to surpass thermally skin-safe temperatures), and the heat of the silicone skin overlay can distract the user from the change in stiffness. A closed-loop control system with a temperature sensor could heat the hydrogel so that it stops heating just above its LCST. This method would save power as well as improve the experience for the user, but the massive increase in fabrication complexity made this technique infeasible for SkinMorph. Additionally, SkinMorph operates on relatively slow time scales which prevent the usage of protective SkinMorph applications intended to respond to immediate threats. A closed-loop feedback system could allow SkinMorph to heat up more quickly, whereas altering the current system to heat up more quickly would unacceptably increase the likelihood of overshooting the safe temperature range.

The social perception of devices worn on the body presents a challenge to the adoption of any on-body technology, including SkinMorph. HCI research into the perception of wearable technology has revealed the complexity of human perception of on-body devices [5]. Some devices such as smartwatches have become acceptable in society. Other devices such as Google Glass have elicited negative responses, even in benevolent use cases such as medical applications [29]. SkinMorph looks so unlike anything commonly worn today that a potential negative social response could prevent the adoption of the technology.
7.2 Future Work

The completed version of SkinMorph suggests some opportunities for future work described here.

7.2.1 Ruggedization and Productization of Design

As discussed in the limitations section, many of the issues of the current version of SkinMorph result from the by-hand fabrication and the delicacy of the silicone skins created by that process. Work towards the ruggedization of SkinMorph is an obvious next step if there is demand for a product in this niche.

7.2.2 Customization

Future versions of SkinMorph could be customized to the user’s body, aesthetic style, and desired use case. The application examples given in this thesis were designed to fit the researchers for ease of data and image gathering. A formal technique for customizing SkinMorph for different body types and body areas could be developed.

7.2.3 User Study

One future goal is to determine whether a device with tunable stiffness would provide useful and interesting feedback to a wearer. SkinMorph may undergo future user studies for qualitative user feedback, although these studies have not happened as of the writing of this thesis (and the studies would not affect the finalized design of this thesis’s electrical system anyway).

7.3 Conclusion

SkinMorph succeeds in being an on-skin device, despite the inherent electrical and thermal challenges of placing heating elements on the wearer’s skin. The device successfully tunes the stiffness of the hydrogel.
This thesis contributes the design and implementation of the electrical control system for a novel on-skin electronic device.

First, a modular control board design resulted in a system able to be controlled in a variety of manners by the user, ranging from a simple toggle switch to Bluetooth control. This design overcame miniaturization, cost, and on-body challenges including electrical and thermal safety.

Second, contribution to the mechanical design of an electrical heating element embedded in a silicone skin resulted in a successful demonstration device. This device and the accompanying photo and video serve as proof of concept for a structurally tunable skin overlay.
Appendix A

Terminology

- **Serial Peripheral Interface (SPI)** A communication protocol which allows electronic chips to talk to each other

- **Integrated Developer Environment (IDE)** A software program which allows programmers to create code, compile it, and potentially upload it to a server or microcontroller as appropriate

- **Human Computer Interaction (HCI)** A field of research exploring how humans interact with computers and electronics, particularly with a focus on the increasing pervasiveness of technology

- **Printed Circuit Board (PCB)** A thin, rigid item with specifically placed lines of copper connecting electrical components. These components are attached to the PCB either with a conductive substance called solder or, much less commonly, mechanically

- **FTDI Programmer or FTDI Breakout** A circuit board which can program a chip over SPI when plugged into a computer over USB as explained in Section 3.4.2.2. FTDI is the company which manufactures many USB conversion chips

- **Lithium Polymer (LiPo)** A specific type of battery which is cheap, relatively easy to source, and thin (in comparison to common AA or D batteries)
• **Surface Mount Technology (SMT) or Surface Mount Device (SMD)**
  A type of circuit component which can be soldered to a PCB without needing a hole in the PCB through which the component’s pins go; an alternative to through-hole components

• **Power Management Integrated Circuit (PMIC)** A circuit component specifically designed for power supply and management applications

• **MOSFET** A metal-oxide-semiconductor field-effect transistor which is a device that acts like a switch, but controlled with an electrical signal instead of with a mechanical lever

• **Radio Frequency (RF)** Refers to electronics which transmit or receive messages in radio waves, such as Bluetooth transceiving at 2.4GHz

• **Near Field Communication (NFC)** A wireless communication protocol that allows two device to talk when very close to each other (usually within 10cm or less)

• **Lower Critical Solution Temperature (LCST)** The temperature below which all components of a mixture are miscible; above the LCST, the hydrogel stiffens, becomes opaque, and pushes water out from the polymer network
Appendix B

Bootloading Instructions

1. Start with an assembled Morphio and a Peripheral Module, both of which have already been checked for shorts (especially in the 20-pin connector).

2. Acquire an Arduino Uno and connect it to a computer with a USB cable. (This process is possible with other Arduinos but is confirmed to work with an Uno.)

3. Set up the Arduino IDE with the following settings:
   (a) Board: Arduino Uno
   (b) Programmer: AVRISP mkII
   (c) Port: whichever port the Uno is attached to

4. Upload the example sketch ArduinoISP to the Arduino Uno.

5. Unplug the Uno while wiring the next few steps.

6. Solder leads to the RESET, MISO, MOSI, and SCLK pads in the bootloading header on the Programming Module. Connect as following to the Arduino Uno.
   (a) Reset: pin 10 on Uno (unless the Arduino ISP sketch has been changed to use a different pin), soldered to the pad closest to the corner of the Programming Module
   (b) MOSI: pin 11 on Uno, soldered to the next pad
(c) MISO: pin 12 on Uno, soldered to the next pad

(d) SCLK: pin 13 on Uno, soldered to the pad closest to the middle of the Programming Module

7. Connect wires to GND and 5V on the Uno, and plug these into GND and VCC on the programming pins on the Programming Module or solder to GND and VCC pads on the Morphio (but not the GND and VRAW pads).

8. Plug the Uno back into the computer.

9. Set the Arduino IDE to verbose mode: Go to File > Preferences and turn on "Show verbose output during upload" by clicking the upload check box.

10. Set up the Arduino IDE with the following settings:

   (a) Board: Arduino Pro or Pro Mini
   (b) Processor: ATmega328 (3.3V, 8 MHz)
   (c) Programmer: Arduino as ISP
   (d) Port: the port that the Uno is attached to

11. Select Tools > Burn Bootloader.

   (a) If unsuccessful, read the verbose error report and check the wiring.
   (b) If successful, unplug the Uno, desolder any temporary connections on the base board, and disconnect the programming module board.

12. Follow Appendix C to program a sketch to flicker the heartbeat LED as a simple test.

   (a) Note: Morphio’s heartbeat LED is on pin 3, not on pin 13 like other Arduino variants, so the example Blink sketch has to be altered.

13. This is now a bootloader Morphio! Remember to switch the Arduino IDE settings back to normal as described in Appendix C before further programming.
Appendix C

Programming Instructions

1. **Important**: Remove any connected traces, batteries, or other power supplies from the Morphio to protect the power supply of the FTDI programmer.

2. Attach the Programming Module to the Morphio. Connect the FTDI programmer to the 6-pin header on the Programming Module. Be sure to align the labels on the board with the labels on the FTDI programmer.

   (a) Another option is to use three hookup wires to connect RX, TX, and GND to the Programming Module. Then, a connected battery powers the board. This arrangement is useful to maintain a wired connection to a computer when the circuit uses more power than the FTDI breakout can supply.

3. Connect the FTDI programmer to a computer over USB. This should power up the board and the programmer. If nothing powers on, revisit step 1.

4. Upload the programming file from the Arduino IDE with these settings:
   
   - Board: Arduino Pro or Pro Mini
   - Processor: ATmega328 (3.3V, 8 MHz)
   - Programmer: AVRISP mkll
   - Port: whichever port the programmer is attached to

   Be sure to remove the programmer before reconnecting the power and traces!
# Appendix D

## Bill of Materials

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<tr>
<th>Component</th>
<th>Board</th>
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<tr>
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Table D.1: The bill of materials for a complete set of boards: one Morphio, one Programming Module, one Bluetooth Module, and one Accelerometer Module.
Appendix E

Prior Iterations

This appendix showcases the quantity of work and number of iterations which culminated in this thesis. It very briefly describes the three PCB iterations before the final Morphio (which itself is described in Section 3.3).

Figure E-1: Morphio’s first revision. The left is the PCB layout and the right is the physical PCB.

The first revision of the Morphio as seen in Figure E-1 served as an early stage prototype. The design was executed before the system requirements were collected due to unavoidable schedule constraints. As the other subsystems progressed in design,
the first revision became obsolete because it could not meet the power requirements of the new heating elements.

![Figure E-2: Morphio’s second revision. The left is the PCB layout and the right is the physical PCB.](image)

The second revision of the Morphio as seen in Figure E-2 was designed after some revisions to the heating element acceptable resistance range. This board was slightly larger than the first revision and was mostly intended to serve as a tool for testing the material and mechanical subsystem designs. This board only powers one heating element output as opposed to the first revision which had two separate outputs. The heating elements are connected with a small two pin connector as opposed to the six pin header in the first version. The programming header was changed to a right-angle connector on the underside of the board, as opposed to the second six pin header in the first version. A 3D printed mount press-fit into the mounting holes on the board to prevent the programming header on the underside of the board from shorting to any surfaces on which the board was placed.

The third revision of the Morphio as seen in Figure E-3 was designed with a variety of changes due to the switch to nichrome wire instead of serpentine copper traces. These changes include a higher operating voltage than the prior iterations, a
different attachment mechanism, and a more efficient power system. The third board has the same dimensions as the second board while having fewer components, so there is a significant amount of unused space on the board. The programming header was a right-angle connector on the underside of the board similar to the second version. Mounting holes were placed in the same locations as in the second revision so that the 3D printed mount could still be used.
Bibliography


