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ChainMail – A Configurable Multimodal Lining to Enable Sensate Surfaces and Interactive Objects

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ABSTRACT

The ChainMail system is a scalable electronic sensate skin that is designed as a dense sensor network. ChainMail is built from small (1"x1") rigid circuit boards attached to their neighbors with flexible interconnects that allow the skin to be conformally arranged and manipulated. Each board contains an embedded processor together with a suite of thirteen sensors, providing dense, multimodal capture of proximate and contact phenomena. This system forms a sensate lining that can be applied to an object, device, or surface to enable interactivity. Under extended testing, we demonstrate a flexible skin to detect and respond to a variety of stimuli while running quickly and efficiently.

Author Keywords

Sensate media, dense sensor network, sensing fabric, electronic skin.

ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms Design and Measurement.

INTRODUCTION

ChainMail is a dense sensor network with embedded processing capabilities that is inspired by the sensory and mechanical characteristics of biological skin. Composed of a discrete set of nodes that are each equipped with a separate microprocessor, the ChainMail system provides a bendable and robust platform that supports dense multimodal capture of proximate and contact phenomena, local and global communication schemas, and local event and signal processing. As described in the Configuration section of our paper, each node contains three pressure sensors to determine vector force, a sound sensor, a light sensor, a temperature sensor, a bend sensor, and a whisker sensor capable of monitoring airflow or proximity.

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In addition to serving as a scalable sensate lining that can add rich contact and non-contact sensing to an object or surface (e.g., for applications ranging from robotics to telepresence), this reconfigurable sensor network offers the opportunity for the exploration and testing of networking, communications, scalability and control questions in large sensor grid deployments.

As a high-density sensor network equipped with embedded processing, as described in the following section, our work is an amalgam of two relatively distinct and nascent fields: high-density sensor networks and electronic skins – an intersection that we term “Sensate Media” [15].

RELATED WORK

Work on sensor networks is not unique. There are an overwhelming number of projects in the literature, but the vast majority of these assume a much lower density of wireless sensing nodes. The sensor design community is also engaged in research on dense multimodal sensing for electronic skins, but their emphasis is on fabrication technologies and flexible electronics without embedded processing, and their results, although impressive, are still far from realistic deployment (e.g., [20, 24]). The HCI community has also developed some platforms termed “skin,” but these tend to be centralized, multiplexed, unimodal sensors more akin to touch screens. We summarize a sample of relevant work below:

- Rekimoto describes a “SmartSkin” capacitive surface. The sensors of the surface feed information back to a single controlling PC, which calculates position and shape from aggregated data [18]. This is a single flat, rigid, unimodal touch sensor, like a large trackpad. Commercial force-sensitive resistor arrays have also been touted as “skins,” [14] although they measure only scalar pressure and are multiplexed without embedded processing.
- Hakoziaki, et al. use inductive coupling to power an RFID-like sensing skin for robot fingertips. Although their system is impressive, it is solely restricted to pressure sensing without distributed processing [4].
- Stiehl built a companion robot, “Huggable,” for deployment in nursing homes and hospitals [21]. In the

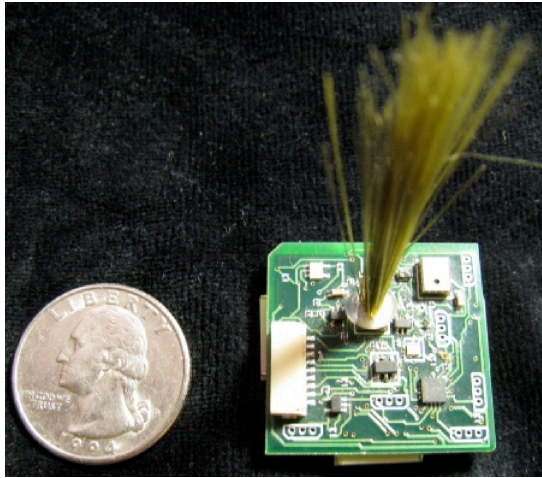


Figure 1. A ChainMail node placed next to a quarter for scale. Note novel whisker sensor protruding from node. (Hall effect sensors are not populated.)

Sensing Modalities of Individual Nodes

ChainMail is loosely inspired by skin - a remarkable multi-sensory organ capable of detecting temperature, pressure, proximity (hair), and light changes (in some species). As such, the modalities that biological skin is capable of sensing heavily, but not exclusively, inform the modalities that ChainMail is designed to sense. Below is a list of stimuli that each node in the ChainMail system can detect.

- *Pressure*: Each ChainMail node carries three distinct FSR pressure sensors. These are calibrated to sense gentle human interaction. Therefore, each node's range of detection roughly ranges from a light finger poke to a moderately heavy hand press. Having three FSR sensors allows nodes to perform rough differential measurements to determine pressure event directions.
- *Sound*: Typical skin does not evince the ability to distinguish sound. However, in our work audio amplitude measurements augment tactile sensing (some pressure stimuli also create an audio signature). We selected the SPM010203NE-3 manufactured by Knowles Acoustic, a surface mount microphone used in portable devices and cell phones, for its small size, power efficiency, and sensitivity [7].
- *Proximity/Airflow*: Biological skin has the ability to distinguish simple proximity and airflow events in its environment using hair. To mimic skin's ability to track these events, and also noting the importance of whiskers to some rodents and other species [3], ChainMail nodes each support a novel "whisker" sensor for tracking proximity/airflow events. The whisker sensor's design went through several iterations. The final iteration, pictured in Figure 1, consists of paint brush bristles glued to a Knowles SPM010203NE-3 microphone. Hot glue was used for its ease of application and because it completely blocked audio signals from exciting the SPM010203NE-3's

element. In contrast to the whisker sensors in Tribble and S.N.A.K.E., ours occupy a much smaller area. While whiskers may be unconventional sensors for HCI, they could be more accepted in robotics, for example.

- *Light*: Light detectors marginally promote the skin metaphor: the skins of several animals are capable of distinguishing small changes in light [1]. More importantly, light sensors provide a smorgasbord of information: sudden changes in a light sensor's state may indicate the shadow of an approaching object, while the signature of a light sensor's waveform could indicate a location (for instance, by querying our light sensor, we observed 60 Hz hum from indoor lighting), etc. We chose a Toshiba TPS851 photosensor for our skin's light detector because of its ultra-small package and because it is specifically sensitized to detect light that excites the human eye.
- *Temperature*: A sensitive temperature measurement could indicate the proximity or touch of a human or animal or signify the presence of a nearby heat source. We chose an LM20CIM temperature sensor. This choice produced mixed results. Although the LM20CIM is small and economical in its power usage [12], it was not as sensitive as we hoped, and it was noisy, requiring us to perform low-pass filtering that took up computational time and may have smoothed over important events.
- *Bend*: The relative bend between nodes is an important value to measure. It gives information about the general topology of the network. To this end, our work incorporates a crude, but novel bend sensor: on each board, we mounted two neodymium magnets (one on the east side and one on the south side of each node) and six Hall effect sensors (three mounted on the north side of the board and three on the west side of the board). This arrangement enables our nodes to triangulate roughly the positions of their neighbors based on magnetic field. In practice, due to the Hall effect sensors' insensitivity to minor magnetic field deviations, this system did not perform as well as desired. Future work would likely deploy a bendy FSR or other, more sensitive device.

Finally, to foster user interaction and provide sensor feedback, each node hosts an onboard, tri-colored LED.

The Sensor Network

The ChainMail system is composed of discrete nodes, which can be conveniently assembled and re-assembled in various configurations, Figure 2. This permits researchers to use the ChainMail system not only to analyze stimuli, but also to perform more rigorous studies, such as examining the dynamic between local and global processing of stimuli.

To facilitate these studies, each node uses a Texas Instruments MSP430F1611 microcontroller to manage sensor scheduling, perform basic data processing, and coordinate separate local and global communication channels.

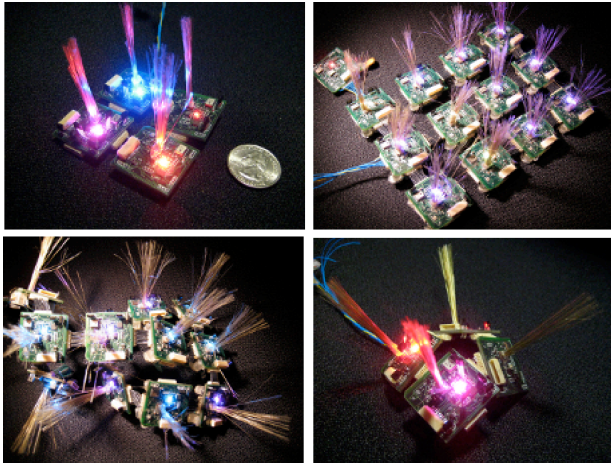


Figure 2. Several configurations of ChainMail nodes.

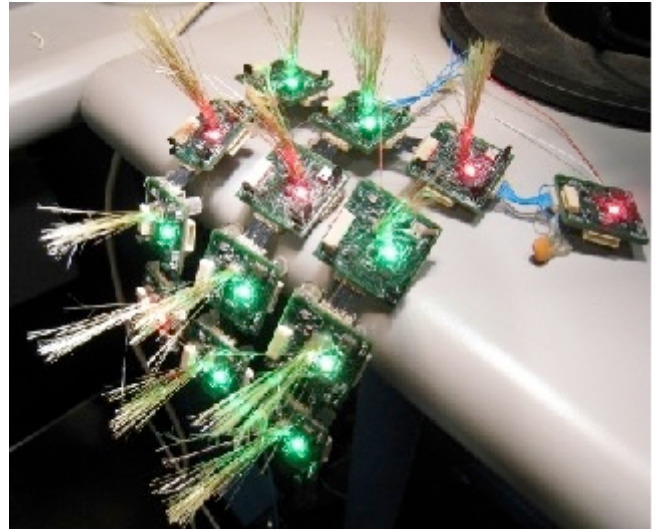


Figure 3. Bendability of the ChainMail system.

Global communication is achieved by an I2C backbone that runs to every node in the network and is coordinated by a single master node. Because I2C messages are serviced as interrupts on the microcontroller, nodes' sending and receiving messages impacts their ability to perform other tasks. Therefore, although our I2C backbone can support baud rates of up to 85,000 bits per second with perfect accuracy, we throttle I2C rates to approximately 48,000 bits per second, which allows us to sample and read sensor states with 8-bit precision for all 156 sensors on a twelve node grid at a rate between 30 Hz and 40 Hz.

Each node in the ChainMail network can be connected to up to four neighbors. We leverage this by implementing a local, asynchronous, peer-to-peer communication scheme. Nodes communicate directly to connected neighbors by passing bits via a ready-enable protocol. The MSP430F1611's high pin count and agile interrupt processing capabilities enable baud rates of over 10,000 bits per second with no observed errors. Providing for peer-to-peer communication addresses many of the scalability issues that restrict our I2C backbone: whereas increased network size reduces the per-node effectiveness of the I2C bus, (assuming well-connected topologies), peer-to-peer communication retains its effectiveness. In addition, separate local and global communication allows us to explore a variety of control hierarchies: we can modify sensor scheduling and microcontroller clock rates, and manage overall node power consumption by selectively "sleeping" and "waking" nodes.

Although we considered insulated springs and flex PCBs for the physical layer interconnects between boards, we eventually settled on nine small wires run between neighboring nodes: one power wire, one ground wire, two I2C communication wires, and five peer-to-peer communication wires.

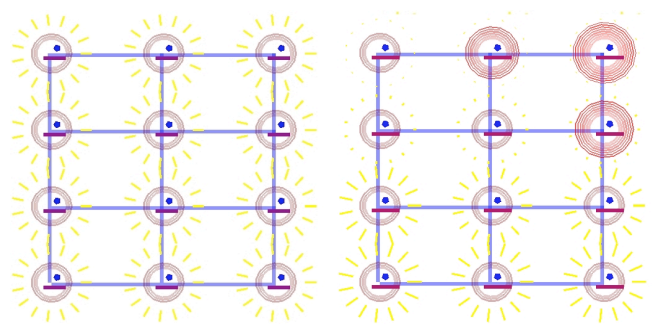


Figure 4. Grid visualization. Left grid shows visualization for twelve nodes with minor audio stimulus under uniform light. Right grid shows upper-right corner of skin undergoing major audio stimulus and upper half of grid shaded, as indicated by number of concentric circles and length of yellow starbursts, respectively.

These wires enabled a reasonable degree of conformal deformation (e.g., see Figure 3) and the connectors enabled easy configuration changes for test and development, inter-board connections were adequate for testing but insufficient for actual deployment. Accordingly, future iterations of our work may incorporate other options.

A visualization program permits the listening PC to receive, process, save and display data sent from the slave nodes. This code provides a form of validation by allowing us to display each node's sensor data across time to assess the skin's functionality and accuracy. This visualization code also eases debugging and increases the usability of the ChainMail system by iconically displaying on a visual grid behavior of each of the individual sensors. As an example, a microphone visualization is shown in Figure 4.

RESULTS: SENSOR DATA AND POWER USAGE

In this section, we illustrate the response of an assembled ChainMail array to diverse stimuli. Although we chose these stimuli specifically to validate overall system perfor-

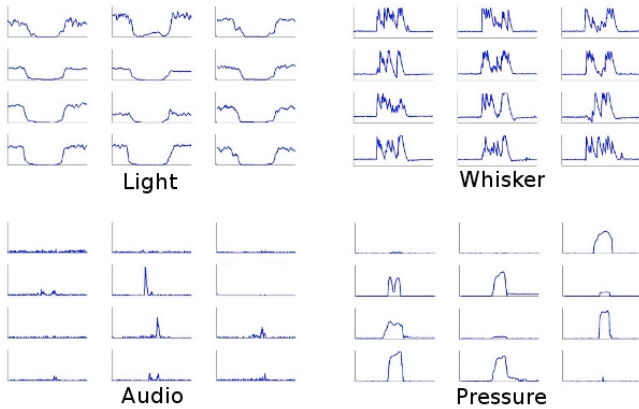


Figure 5. Readings from four sets of sensors for twelve ChainMail nodes arranged in a 4x3 grid as a hand descends, presses on, and releases from grid. Plots span 6.5 seconds, and are globally normalized for each sensor family.

mance, we would additionally expect to encounter them in potential interactive objects or robotic skin applications.

Basic Hand Press

We recorded sensor data as a hand approached, descended, pressed on, and pulled away from a four-by-three node grid. The light, whisker, microphone, and pressure data from this experiment are presented in Figure 5 (we omit bend and temperature data for space considerations). Because a hand is neither completely flat, nor uniform, the figures (particularly the pressure data) indicate that the response of the sensors is quite heterogeneous.

Progressive Hand Press

We need not limit ourselves to the basic hand gesture described in the previous section. While the hand gestures in the previous section deal with a hand’s carefully and uniformly pressing on the entire skin or a section of the skin, we also have the ability to explore more heterogeneous gestures. Figure 6 present light, whisker, temperature, microphone, and pressure data respectively from a hand’s pressing on the left-most column of the skin, progressively rolling onto the right side of the skin, and rolling back.

The non-uniformity of the hand stimulus can most easily be seen from the whisker responses, Figure 6B. Whisker sensors on the left column of the skin record excitation before whisker sensors in the right column. Initially, we thought that some pressure sensors may have broken. However, repeated tests confirmed that they were completely functional. Therefore, we conclude that the lack of response exhibited by these nodes’ pressure sensors is attributable to the non-uniformity of the stimulus. This interpretation is confirmed by the audio plots of our nodes.

As noted in the Related Work section of this paper, many of the projects that form the corpus of the sensate skin literature focus almost exclusively on pressure sensing. Therefore, they are prone to missing proximate events – nearby stimuli that never trigger pressure sensors.

ChainMail’s light sensors, sound sensors, and whisker sensors also have the ability to detect stimuli that make little or no contact with our network.

Although acoustic waves from abrupt sonic transients have a relatively distinct dynamic boundary when they pass over our array (which can enable simple sound-source localization) [6], it does not make sense to think of certain stimuli, such as a continuous sound, as having an “edge”. However, other stimuli have very well-defined edges, and detecting an event’s edge may be very useful. For instance, changes in a shadow’s size or darkness may indicate an object’s approach or departure. Clearly, a single node cannot determine a shadow’s edges, or, its dimensions. However, by linking several nodes together and sampling the light sensor of each, we can find the rough boundaries of a shadow. Shadow edges can be detected either through real-time internode messaging on the skin or via offline analysis.

In dark environments, this approach can be inverted - the light sensors can detect increasing reflection from the onboard LEDs off of approaching nearby objects. Figure 7 presents the data from an eleven-node ChainMail grid as a hand casts a shadow over part of the network (initially) and

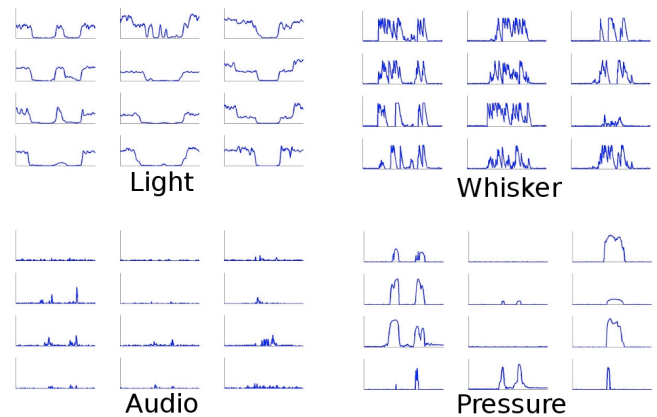


Figure 6. Readings from four sets of sensors for twelve ChainMail nodes arranged in a 4x3 grid as a hand rolls from the left side of the system to the right and back. Plots span 8.25 seconds, and are normalized for each sensor.

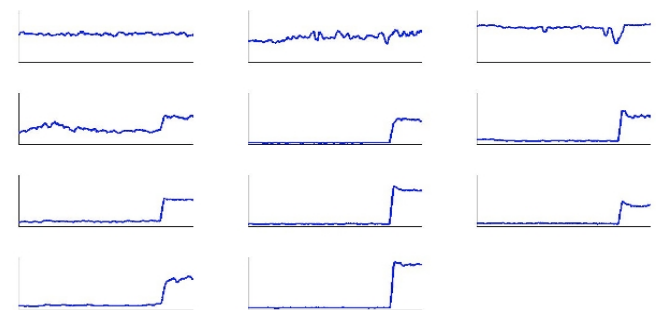


Figure 7. Light sensor waveforms of an eleven node ChainMail grid while a hand roughly casts a shadow over the grid’s bottom-right corner.

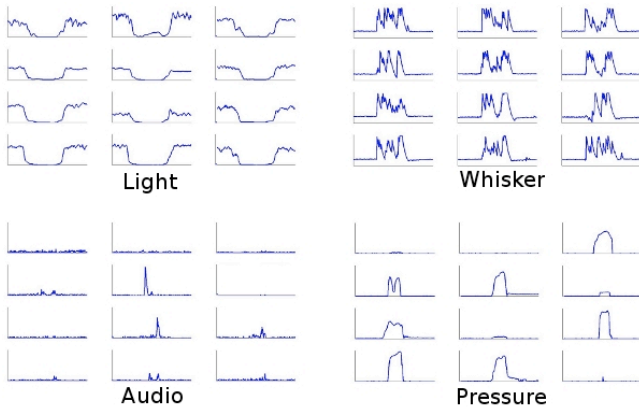


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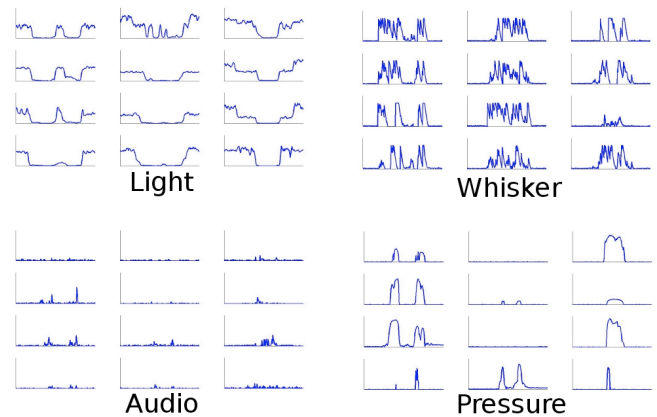


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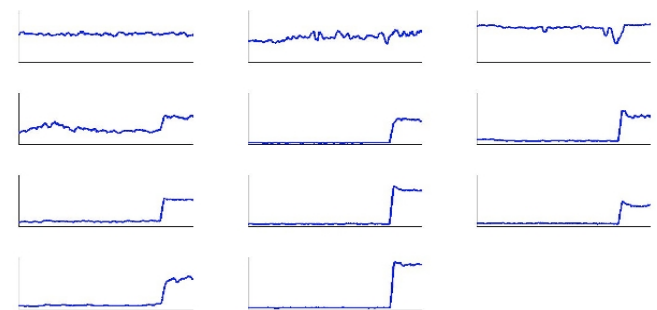


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Figure 8. Whisker data from four nodes as a hand passes over each sequentially. Top Panel: Three hand sweeps in a row. Bottom Panel: Zoomed view of first hand sweep where one can see individual fingers passing over the whiskers.

is then removed. Due to lighting angles, in the experiment the node in the second row and first column of Figure 7 was partially obscured - a feature that is apparent in its light sensor's output waveform. In the context of the other nodes' data, this allows us to roughly infer positions of occluding objects relative to light sources.

Additional experimentation showed that ChainMail's whisker sensors also served well in detecting the edges of proximate events. Figure 8 presents the data from four nodes chained in series as a hand skims over their whisker sensors three times. With *a priori* information about the spacing between these nodes, we were able to estimate hand speed, Table 1.

The high sensor density of ChainMail and its communication infrastructure provides incredible detail on the nature of even minor interactions. ChainMail's whisker sensors can quantify both the intensity of the interaction, and its direction, speed, and path over time, Figure 8 and Table 1.

Power Usage

In full operation, individual nodes consume up to 250 mW of power. This figure is dominated by a tri-colored LED and six distinct Hall effect sensors used for measuring bend. For some applications, this may be excessive or even wholly unreasonable. We might achieve substantial power savings by physically removing several sensors or LEDs from each node - as we eventually did with our magnetic bend sensors. However, this solution is hardly desirable - it reduces the overall functionality and requires substantial effort to implement or reverse. Fortunately, there is another, more flexible option - we can adjust tri-color LED output and dynamically throttle the rate of our microcontroller's

clock and transition into a low power mode, correspondingly. For our particular part selection, such steps can reduce our microcontroller's power usage by a factor of four orders of magnitude [23] - recent developments by TI and others are reducing current needed by low power modes much further in upcoming MSP-family products.

We demonstrate the effectiveness of this strategy by connecting five nodes in the shape of a '+'. Nodes A, B, C, and D are located on the outer edges of this '+' and Node E is at the center. All nodes are initialized into their lowest power states. Additionally, we set an interrupt on Node E's whisker sensor. When E detects that its whisker sensor has been depressed three times, it sends a message via our custom-designed peer-to-peer protocol to A.

	Node A	Node B	Node C	Node D
Time at Which First Significant Stimulus Noted (s)	5.3	6.1	6.7	7.2
Speed When Compared to A (cm/s)	-	4.1	4.7	5.2
Speed When Compared to B (cm/s)	4.1	-	4.7	5.2
Speed When Compared to C (cm/s)	4.7	5.5	-	6.6
Speed When Compared to D (cm/s)	5.2	5.5	6.6	-

Table 1. Hand Speeds Calculated from Whisker Sensors. Average Hand Speed: 5.3 cm/s.

Upon receiving this message, A switches into its highest power mode at its fastest clock rate. After receiving five, seven, and nine interrupts on its whisker sensor, E sends similar wakeup messages to Nodes B, C, and D respectively. Additionally, after detecting nine whisker events, E switches from its low power mode to run at its most power hungry state. Table 2 presents the current consumption of the network composed of Nodes A, B, C, D, and E when undergoing this experiment. Notice how dramatically the power consumption of the overall network changes as nodes change their states. (In order to highlight our results, none of the nodes' six Hall effect sensors are populated - if we had included these six sensors, theoretically they would have consumed an additional 48 mA.)

While such a result provides insight into potential power regulation schemes on our skin, it also hints at possible future control mechanisms for our skin, touched on in the following section. Such control mechanisms could play a part in rejecting spurious stimuli, scoping processing, and regulating information flow.

A more comprehensive display of ChainMail's capabilities and additional data captured via this system, is available [11].

CLOSING REMARKS AND FUTURE WORK

The overall ChainMail system functions well. It sustains high data communication rates, is relatively bendable, and provides significant multimodal insight into various stimuli and tactile gestures, indicating its potential utility. However, the ChainMail system is not a fully mature project. Additional work on the ChainMail system to address existing infrastructure and sensing issues as well as exploring further applications would greatly increase its value.

In particular, our results suggest that we should reconsider our temperature sensor and bend sensor. The temperature sensor's position on the node made immediate contact with stimuli difficult, reducing the value of its readings. Our bend sensing scheme should also be improved. Although theoretically, determining relative bend between nodes from differences in their magnetic field should work, in practice, our Hall effect sensors were highly directional and not sensitive enough to capture differences in subtle movements. Future iterations of this work will likely rely on an optical or active AC magnetic sensor or a mechanical link - e.g., a bendy or stretchy FSR to detect bend between neighboring nodes. In addition, although adequately flexible and well suited to swapping nodes out during development, the wire interconnects between nodes are relatively fragile. We have considered moving to flexible circuit board interconnections, insulated springs instead of wires, or even fabric with conductive thread to increase robustness while maintaining flexibility.

Int.'s on Node E	Node A Mode	Node B Mode	Node C Mode	Node D Mode	Avg. Total Current Consumed
0	Lowest Power Mode	Lowest Power Mode	Lowest Power Mode	Lowest Power Mode	5.144 mA
3	Highest Power Mode	Lowest Power Mode	Lowest Power Mode	Lowest Power Mode	7.558 mA
5	Highest Power Mode	Highest Power Mode	Lowest Power Mode	Lowest Power Mode	9.873 mA
7	Highest Power Mode	Highest Power Mode	Highest Power Mode	Lowest Power Mode	12.198 mA
9	Highest Power Mode	Highest Power Mode	Highest Power Mode	Highest Power Mode	17.288 mA

Table 2. Current Power Consumption from Skin Patch Wakeup Routine

As described in this paper, the ChainMail system provides a solid platform that incorporates reliable, fast communication protocols, embedded processing, high sensor density, and physical bendability. Future work will leverage these capabilities to enrich ChainMail's application space. In particular, with additional work on synchronizing ChainMail's nodes, it should be possible to localize audio stimuli from timing differences in microphone waveforms of nodes arranged in a grid.

In addition, because of its distributed processing power and separate communication schemes, ChainMail can become an *in situ* compact platform for the verification and development of distributed sensor network control schemes. Future work on ChainMail may therefore focus on algorithmic inquiries into scoping processing and cooperative and competitive network behavior. Further research in this area is relevant to making ChainMail scalable to larger areas - e.g., conserving backbone bandwidth by trading off local versus global event processing and adaptive duty-cycled and interrupt-driven wakeup operation to keep power requirements minimal.

Finally, ChainMail is configured to sense, record, and report events in its environment. Currently, we store and present these data. However, future work may extend the ChainMail system with actuators, treating it as a multimodal interface to control objects in a user's environment.

Although the basic ChainMail system presented in this paper provides multimodal insight into a variety of stimuli and tactile gestures, the extensions of ChainMail hold academic and practical promise that should further enrich its usefulness.

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