Distributed Sensor Networks as Sensate Skin

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Abstract

We have designed and constructed a hardware test bed to explore the application of a dense, multi-modal, peer-to-peer sensor network as an electronic "skin"; a sensate lining that covers an object to sense, process, and coarsely classify local stimuli. Resulting parameters can be routed between nodes (which we term skin "patches") neighbor-to-neighbor to a portal for external analysis and/or produce a local response with a set of actuators built into each patch. The resulting device is a roughly 33-cm diameter sphere tiled with such patches. Each patch sports an array of vibration-sensitive whiskers, sensors for local pressure, light, sound, and temperature, as well as actuators for a full range of colors, vibrations, and sound. All these sensors and actuators fall under the control of a dense, distributed sensor network, as each patch is connected to its neighbors. Geometrically, this device, termed "Tribble", resembles a soccer ball, where each face is a single patch of skin.

Keywords

Distributed, sensor network, sensate skin, whisker.

INTRODUCTION

Biological skin, such as that which covers our own bodies, is a remarkable feat of sensing 'technology' – it incorporates many sensing modalities (chemical, thermal, mechanical, etc.) into a dense substrate (~ 250 sensors/cm^2 at the fingertips [8]), which, in addition to sensing, serves many other functions (e.g. protection from pathogens and radiation, waterproofing, heat exchange). Furthermore, this biological sensor network processes data through complex interactions at many levels throughout the nervous system; i.e., within the skin itself, within the spinal cord, and within the brain's somatosensory cortex [4].

These specifications present an intriguing, yet relatively unexplored regime of distributed sensor networks. For the purposes of this paper, a distributed sensor network is defined as a collection of many independent sensing nodes, each of which is imbued with modest processing and neighbor-to-neighbor communication capabilities. This is somewhat different than the usual notion of a sensor network, in that the emphasis is not so much on power conservation and wireless communication, but rather on the distributed nature of the system [2, 3, 13]. When applied to the regime of sensor density, multi-modality, functionality, and physical form embodied by biological skin, this notion of a distributed sensor network is differentiated even further.

With this in mind, we set out to build Tribble (Tactile Reactive Interface Built By Linked Elements or The Robotic Interactive Ball-Based Living Entity), a spherical robot covered in 'electronic' skin imbued with rich sensory inputs and the ability, albeit somewhat limited, to express its state and act on the world. This paper details the functional characteristics of Tribble and introduces further directions in which we plan to take this work.

Motivation

The motivations for building Tribble stem from our recent work with our Pushpin sensor network test bed, a collection of approximately 100 sensor nodes equipped with infrared transceivers and conductive pins to draw power from a powered 'corkboard' [9], upon which they can be arbitrarily distributed. Specifically, we are interested in the regime of sensor networks we call electronic skin, in which nodes are distributed densely (100 – 1000000 nodes per square meter) over a surface or throughout a material and are able to emulate the functionality and characteristics of a biological skin. Although many of the principles of more traditional sensor networks carry over to this regime, there are important differences; for example, a large centralized power supply is no longer out of the question and communication is not restricted primarily to radio.

An immediate application of such a sensor network is as a skin for a mobile robot (e.g., [6, 10]). In this scenario, the skin would manage the torrent of incoming sensor data at the level of the sensors themselves and pass on to the robot's central controller only more refined feature extraction results. Tribble is a test bed upon which we will develop and validate heuristics and algorithms for distributed data reduction and decentralized real-time decision making.

Background & Previous Work

The development of electronic skin technologies is a growing and diverse research field. Workers have sought to cover a variety of surfaces with dense arrays of a wide range of sensors. We present here a brief overview of some of the most notable methods and results.

Some research has been conducted looking into sensate skin for mobile robots, although to the best of our knowledge none has made explicit use of the notion of sensor networks. Collaborations between Tokyo University of Agriculture & Technology and the University of Tokyo have resulted in two novel manufacturing and sensing techniques to for wireless tactile sensing elements [6, 20]. NASA's Robonaut project employs many sensors on a telepresence robot to provide feedback to the operator [15]. On a smaller physical scale, there are a variety of efforts concerning artificial finger tips, among them are [7, 18, 21].

Aside from robotics, there is considerable interest in sensate skins for transforming everyday surfaces into interactive spaces [12]. One well-explored method involves a row-column matrix of multiplexed capacitive sensors [5, 14, 17]. This method has also been applied to other types of pressure sensing, such as force-sensing resistor arrays [11].

MEMS devices have also been integrated into skin-like structures, for example, a MEMS skin to detect shear-stress over a surface due to airflow, for possible use on an airplane wing [19], where the term "smart skin" is already over a decade old.

Most of the work just described focuses on new transduction methods, novel manufacturing techniques, or centralized systems integration. In contrast, the focus of the present work is distributed systems integration.

EXPERIMENTAL APPARATUS

Geometrically, Tribble resembles a large soccer ball (i.e., an inflated version of a polyhedron known as the truncated icosohedron, which is composed of 20 hexagonal faces and 12 pentagonal faces). Each of the 32 faces can be considered as an individual 'patch' of skin. The patches screw into a plastic frame and can be individually removed and/or replaced at any time during Tribble operation. All of Tribble's processing capabilities reside in distributed form in these patches; there is no central controller or master patch.

Four NiCd D-cell batteries and accompanying voltage regulation circuitry are suspended at the center of the frame, providing approximately 5000-mAh distributed among all 32 patches via a star configuration of RJ22 cabling emanating outward from the center. Tribble can also be powered by an external DC power supply. See Figures 1, 2 and 3.

The same RJ22 cabling also provides a global communications bus as a means of programming and debugging all patches in parallel from a personal computer. The global bus is not otherwise used by the patches themselves during normal Tribble operation. Rather, the patches communicate neighbor-to-neighbor. The same screws that mechanically secure a patch to the frame also provide a 115200-kbps communication channel to each of the five or six neighboring patches via a direct electrical connection through conductive brackets fixed to the frame. These communication channels are fed through a multiplexer to the patch's 8-bit, 22-MIPS microprocessor, located on the underside of the patch.

This microprocessor locally manages the patch's sensor data collection, actuator response and communication with neighboring patches. For actuation, each patch has at its disposal a vibrating pager motor, a RGB LED, and a small speaker. As for sensing, each patch is equipped with 7 (pentagonal patches) or 12 (hexagonal patches) piezoelectric whisker sensors, three force sensitive resistor (FSR) pressure sensors (enabling determination of the magnitude and center of applied force), a solid-state temperature sensor, a light-dependent resistor (LDR) light sensor, and an electret microphone. A hard, diffusive polyethylene shell covers the exposed side of each patch. The whiskers consist of nylon/polyester paintbrush bristles extending from a piezoelectric cantilever and protruding from the protective shell. Polyurethane foam transduces pressure applied on the shell to the FSRs below. See Figures 4 and 5.

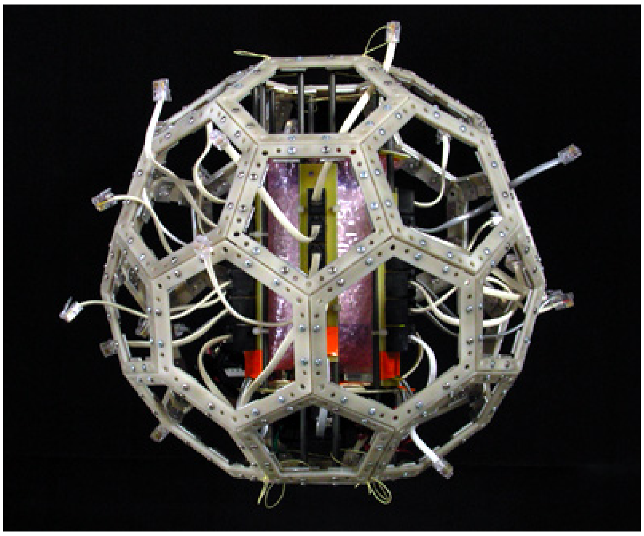

Figure 1. Tribble frame with no patches.

All told, Tribble has 516 channels of 10-bit sensor input being sampled at approximately 1000-Hz per channel, on average (actual sampling rates depend largely on the sensor being sampled.) Thus, the Tribble as a whole has approximately 5-Mbits/second of sensory bandwidth. (An empirically tested upper-bound of Tribble sensory bandwidth is actually closer to 22-Mbits/seconds, but this is impractical as there would be no CPU resources left over to process the data.) In comparison, the previously mentioned Robonaut humanoid telepresence robot has approximately 150 sensors on each of its two arms [15].

BEHAVIORAL SYSTEM & SOFTWARE DESIGN

The software underlying Tribble is distributed among its 32 patches of 'skin,' residing in the 32-Kbyte on-board flash memory of each patch's 8-bit microcontroller. All patches are loaded with essentially identical code, the only exceptions being a two-byte random seed and slight variations between hexagonal patch and pentagonal patch code due to the differing number of neighbors and whiskers. Although they all start out in similar states, the patches' behavior quickly differentiate due to variations in their sensor data. Thus, patches are relatively independent and must actively communicate to keep track of neighboring patches' states. It is in this sense

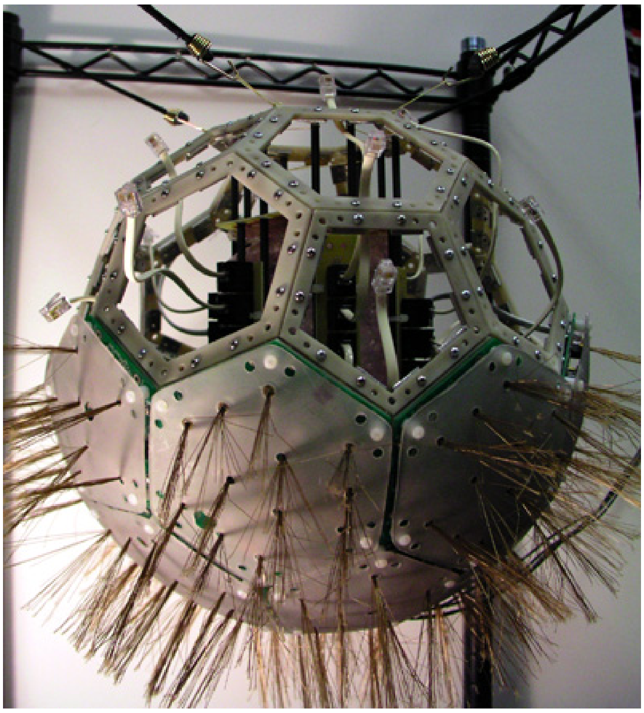

Figure 2. Tribble frame with some patches attached.

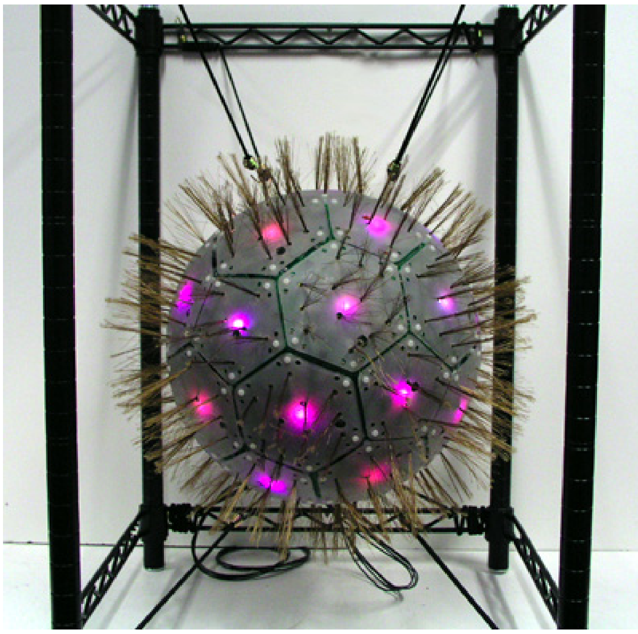

Figure 3. Tribble frame with all patches attached.

that Tribble is a distributed sensor network.
Briefly, the software is divided into two main threads of operation – an interrupt-driven communication system and a sensing/actuation system.

Communication

The communication system sequentially scans all the channels to neighboring patches in such a way as to provide some guarantee of receiving a packet from a neighboring patch regardless of which channel it is currently scanning when the neighbor starts sending the packet. In any case, all communication between patches is predicated on a request/acknowledge protocol and an 8-bit cyclic redundancy check (CRC). In addition to a channel for each of its neighbors, a patch can monitor the global bus for commands issued to all patches in parallel from a desktop computer. Similarly, every patch is equipped with a stereo jack accessible through a hole in the outer shell, allowing each patch to be individually accessed from a desktop computer. Under normal operating conditions, neither of these channels is used; they exist primarily for debugging, uploading new code to the patches, and downloading data to a desktop environment.

Sensing

The bulk of the functionality and behavior of Tribble emerges from the sensing and actuation system. The inherent trade-off to be made here is between the sampling rate of the sensors and the complexity of the output derived from the sensed data; a higher sampling rate necessarily reduces the number of CPU cycles devoted to processing the sampled data, determining what actions to take based on those results, and then executing the desired behavior. This trade-off can be dynamically balanced in software by adjusting the aggregate sampling rate (samples per second per patch, summed over all channels), which can be set as low as 300-Hz and as high as 72-kHz. Once the aggregate sampling rate is decided, it must be divided among all the sensing channels on the patch, as the different sensor modalities are suited to different acquisition intervals. This is also dynamically determined in software, such that all channels are sampled at a constant rate. Conflicting requests by different sensor channels to be sampled (there is only one ADC) are avoided by choosing relatively prime sample periods. Table 1 lists the approximate sampling rates currently used.

sensor modality	# sensors	samples/sec/sensor	window size
temperature	1	0.5-Hz	8
light	1	4-Hz	64
pressure	3	34-Hz	64
whisker	12 (7)	593-Hz	64
microphone	1	9978-Hz (12943-Hz)	256

Table 1. An example of dividing an aggregate sampling rate of 17200-Hz among all the sensing channels for a single hexagonal patch. Items in parentheses refer to pentagonal patches.

Actuation

At the sampling rates listed in Table 1, there are enough remaining processor cycles to manipulate the incoming sensor data in simple, yet useful ways. For example, windowed

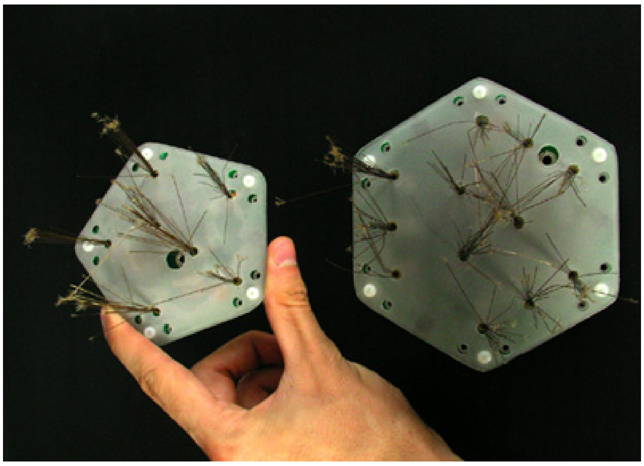

Figure 4. Individual patches of Tribble skin.

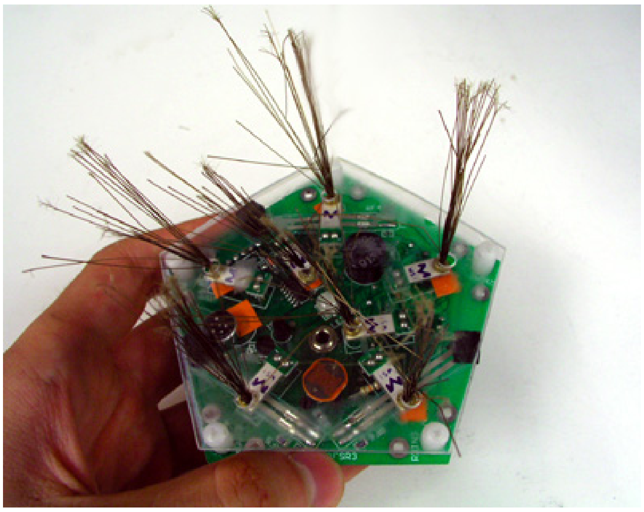

Figure 5. A pentagonal patch with a clear shell. All sensors and actuators are visible except for the temperature sensor and the vibrating motor.

averages are kept for each sensor channel on each patch. Note that, although each sensing channel is sampled at 10-bits, for reasons of speed only the most significant 8-bits are used. Actuation of a patch's vibrating motor, RGB LED and speaker are mapped in software according to this information and executed in parallel with the sensing routines.

The vibrating motor and each color of the RGB LED are pulse-width modulated, allowing for a wide range of vibrotactile and color feedback, respectively. The speaker can replay at 8-kHz any of approximately a dozen short 8-bit sampled sounds. Furthermore, additive sound synthesis is used to create sounds with arbitrary timbre [16].

INITIAL DEPLOYMENT

Tribble, as just described, is complete. Quick-turnaround programming tools are in place to program all 32 patches in parallel and query the system during operation.

In addition to acting as a testbed for distributed sensing and actuation, Tribble was designed to be an evocative object for interactive art venues, bringing the concept of sensor networks to the general public. Accordingly, an early robustness test and the first public appearance of Tribble was held at a robotic art show in New York City over a weekend in July 2003 [1]. For this event, Tribble was suspended in the middle of an open rectangular frame and was easily accessible to direct manipulation by all passers-by. See Figure 6.

Tribble used a simple mapping of sensor input to actuator output based on threshold comparisons of the most recent sensor channel value to that sensor channel's windowed average. For example, quickly casting a shadow over a patch of Tribble triggered the fading sequence of the patch's green LED. However, slow changes in ambient light had no effect. A cricket chirp triggered by petting any of the whiskers on a patch served as an immediate and distinct reaction that the audience could easily grasp. Other cause-effect relationships where not as discernible given the limited amount of time most of the audience spent at the venue and the chaotic ambient conditions caused by large crowds (e.g., jostling, constantly varying noise level, changing lighting conditions).

Figure 6. Tribble made its first public appearance at "ArtBots: the Robot Talent Show" in July 2003 [1].

FUTURE WORK

The overhead for prototyping behaviors on Tribble is now low enough that we are turning our attention to higher level heuristics and more general classes of behavior. In particular, we are interested in three types of algorithms.

- Heuristics taking advantage of the multi-modal nature of Tribble's skin. For example, rolling along the ground and being petted in a circle are difficult to differentiate by examining only the whisker sensor data, but may be disambiguated by including pressure and light data as well.

- Algorithms that desensitize and inhibit sensor response when appropriate, in analogy to acclimation behavior in the human sense of touch. For example, the sensor should acclimate to a light breeze and pay attention to more salient events.
- Simple predictive actuation techniques. For example, selectively lighting the patch that will next come in contact with the ground as Tribble rolls requires shared knowledge across more than one patch.
- Although Tribble illustrates the concept of a skin as a multi-modal sensor network, its sensor density is still extremely low, especially in contrast to what nature routinely achieves. Future investigation will explore technologies that can scale to higher node densities.

CONCLUSIONS

We have built and validated a multi-modal, high-through-put, distributed sensor network-based electronic skin. A flexible behavior engine allows for real-time reaction to complex environments and quick prototyping of mappings between sensor inputs and actuator outputs. Future directions include multi-modal heuristics, excitation and inhibition algorithms and predictive actuation based on distributed consensus.

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