

Physiological Monitoring by “Credit Card”

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Abstract

An ultra-thin and flexible physiological monitoring system has been designed that is suitable for use in a wide range of applications from sports training and performance assessment to the home health monitoring of the world's aging population. Key aspects of the design include: embedded garment sensors with a simplified 1-wire bus structure; a miniaturized ultra-thin, self contained electronics/controller module; and a wireless interface for the real-time remote data monitoring and analysis.

Keywords: health monitoring; embedded sensors; low power electronics; ultra-thin electronics; flexible electronics; sensor system; apparel electronics

Introduction

The need for real time monitoring of human physiological functions is becoming increasingly important due to a rapidly increasing over age 50 population and the general trend in younger generations for fitness training. Also both amateur and professional athletes are pushing their bodies to the limit so real time monitoring of their health status is paramount. Such monitoring has to be done in a non-intrusive, non-motion inhibiting manner; yet provide reliable sensing and signal processing to transmit or store relevant information for the physician, coach and/or the individual. Key to this monitoring is the development of the appropriate sensing system and the associated electronics. A particular intriguing solution to this problem is a wearable-smart garment provided the sensors and electronics can be configured to provide reliable data

while being un-intrusive to the wearer and can be safe or removed during garment cleaning cycles.

Clothing containing sensors to monitor bodily physiological functions is not new and several references to smart clothing have appeared in the literature [1]. The major problem to date with electronically active or smart clothing is that the monitoring control and powering electronics always appears as a relatively large box (electronics plus battery) attached to the clothing or in some cases a wrist band or a belt. Wires typically run from the garment containing the sensors to these boxes. Other manifestations have actually embedded these boxes into the garment thus causing difficulties in laundering. In some cases the sensors have to be attached directly to the body, such as the case with wearable heart monitors, using adhesives or conducting gels.

Approach

The sensor/monitoring system described in this paper eliminates or circumvents many, if not all, of the issues or limitations described above. In our system the sensors are strictly contact or proximately being embedded in a form fitting garment similar to exercise togs. The electronics modules can be easily removed for garment maintenance (laundering). The electronics is truly un-intrusive being literally in its ultimate configuration the size of a credit card (55 mm wide x 85mm long x 1mm thick) and more flexible. A range of thicknesses, from 6 mm (6 credit cards) down to 1mm or less, is planned for this credit card sized module depending upon cost targets, the style of electronics (conventional or thinned [2]) (frequency and range of transmission, number of functions monitored, and module display if used). In all cases the thickness reference are inclusive of the rechargeable lithium polymer battery.

The degree of thinning is determined by several factors, as mentioned above, and is, of course, dependent upon the needed degree of comfort and ease of use required by the wearer. The module in all forms is extremely light weight, weighing less than 25 grams (<1oz) battery included. In the ultra-thin form, the weight is 10 grams or less (exactly like a credit card). Figures 1, 2, and 3 illustrate the concept. The module will be highly functional and will have the capability of telemetering a range of biological information over a wireless link. Such information includes: humidity, temperature, respiration, pulse, skin resistance (moisture loss), blood pressure, and motion.

Physiological Monitoring

Several candidate physiological activities may be monitored. Some sensors are located on the wearable garment while others are attached to or an integral part of the electronics module. Other optional sensors could be made part of a wrist band or wearable cuff. All sensors are managed by a small central electronics module that is attached in a special pocket in the garment so as not to interfere with the users' activities. The system is modular and the optional wrist (or ankle) sensor suite may be detached without affecting the operation of the controller and garment sensors. The text below

describes a proposed configuration which can easily be modified to meet the range of potential physiological monitoring system application areas from sports training and medicine to home health care for the elderly.

Garment Sensors are key to the operation of the physiological monitoring system and to its ultimate performance. The main sensors are:

- **Body Temperature.** Several temperature monitors are mounted in various critical locations around the torso and linked by a 1-wire common bus. A temperature sensor is also located in the controller to monitor the temperature of the ambient environment.
- **Perspiration.** Two humidity sensors are installed – one mounted on the controller and one near the axilla. The signals are conditioned and linked to analog to digital converters (ADCs) connected to the 1-wire common bus.
- **Respiration.** Two strain gauges are mounted to stretchable electrical wires around the thorax and abdomen to monitor rate and depth of respiration. The signals are conditioned and linked to an ADC connected to the common 1-Wire bus. The strain gauges are embedded in the wearable garment.

The ultra-thin and light weight electronics module is placed in a special pocket manufactured into the garment to afford ease of subject use and to provide interconnect protection during physical activity, yet provide easy removal for laundering. Embedded wires from the garment sensors and the optional wrist sensor suite connect to the electronics module. Sensor and conditioned data is either relayed by an infrared or wireless communications link to a portable computer (PC) or monitoring station. If communications cannot be established, the data is stored in local memory awaiting future transmission or in a micro PCMCIA card which could be then be subsequently downloaded to the PC. The batteries are user replaceable and power the electronics module, the embedded shirt sensor suite, and the wrist sensor suite.

- **Microcontroller.** An 8-bit micro-power controller is used to monitor and control the sensors, collected data, process the data, store the data in memory, and initiate data transmission. The microcontroller operates continuously. The microcontroller may also drives a liquid crystal display (LCD) or other display located on the wrist sensor suite. This display could also function as a watch when not displaying health monitoring information.
- **Memory.** Flash Memory on the electronics module is used to store data for later transmittal to a PC. Data will be monitored dynamically every minute and the final results stored in memory.
- **Communications.** Real time or stored data will be downloaded to the PC or monitoring station via a wireless communications link, an infrared relay link or by USB cable. The data rate for transmission would be less than 1K- Baud. If communications cannot be established, the data is stored in local memory for later download.

The Wrist Sensor Suite is self powered and communicates to the electronics module. Embedded wires or a wireless interface connect the Wrist Sensor Suite to the central electronics module. Some possible sensors for the Wrist Sensor Suite are listed below.

- **Galvanic Skin Response.** A simple conductivity sensor is used to detect the galvanic skin response (as in a lie detector) and mounted around the wrist sensor suite band. Signals are conditioned and linked to an ADC connected to 1-wire common bus. The data is collected during a blood pressure reading to insure the sensor is in full contact with the skin.
- **Blood Pressure-Pulse.** A wrist based sphygmomanometer is mounted to the Wrist Sensor Suite to monitor systolic and diastolic blood pressure as well as pulse. Signals are digitized by the sphygmomanometer controller and sent to

the central electronics module. Due to potential discomfort, the system is actuated intermittently.

- **Pulse-Saturated O₂.** One transducer would be mounted in the wristband or wrist cuff to measure Saturated O₂ (0 to 100%) and pulse via pulse-oximetry. Signals are conditioned and linked to an ADC connected to the common 1-wire bus. The sensor can be attached to the ear or finger.

Construction

A light weight shirt is used with the sensor system embedded on the inside using stretchable wiring for communications, power, and strain gauges. The system is wired horizontally through the shirt to provide comfort and reduce any potential damage to the electronics. The additional weight will be negligible.

Many sensors are linked to a 1-Wire Common Bus and queried for data download periodically. The 1-Wire common bus is constructed of thin metal (1 mil) with 3 wires to handle power, ground, and data I/O. Sensors chips are thinned and bump-bonded to the metallization on the polyimide substrate. The sensors are then glob-topped to seal against moisture and provide stain relief. Thin polyimide will provide enough thermally conductivity so it will not interfere with the measurements.

An existing wrist based sphygmomanometer will be modified to incorporate the pulse-oximeter and an LCD (if needed) to display functions.

A flexible, reliable electronics module with integrated power source is key to full system implementation. The new approaches outlined in the results below will provide the reduced size, high performance module necessary to make wearable health monitoring systems truly practical. While the initial efforts have been focused on low profile planar type modules, the flexible substrate, thinned-die technology is also amenable to die and module stacking. This use of the third dimension could reduce the modules footprint area and allow it to be placed in other sports or health related equipment.

Results

Progress towards the realization of the completely integrated physiological monitoring or homeostasis verification system has progressed on several fronts.

We have shown that 0.1 mm thick flip chip assemblies on flex both with and without underfill were extremely reliable, surviving thousands of thermal cycles from -55°C to $+125^{\circ}\text{C}$. Even though the non-underfilled assemblies were extremely reliable, the selection and application of a low modulus [2, 3] underfill provided additional stress reduction on the solder joints so that no solder joint failures occurred after 4,000 temperature cycles (after which the test was terminated). These thinned die on flex circuit modules were assembled in a conventional manner. The flex substrates were photolithographically patterned to hold and daisy-chain interconnect four large (10mm x 10mm) test die, each containing 1,368 eutectic tin-lead solder bumps on a $250\mu\text{m}$ pitch. The flex was held flat during the oven solder reflow process by a vacuum fixture. Following reflow and cooling underfill, if used, was applied and cured with the assembly still on the vacuum fixture. Lifetime testing was conducted using a special test board containing four of our 30 x 30mm modules. Such a thinned microcircuit assembly is shown in Figure 4.

We have replaced the one- or two-conductor layer flex circuit board ($50\mu\text{m}$ thick, Dupont Pyralux® AP copper-clad laminate) described above with a thin-film polyimide substrate containing four conductor layers and five dielectric layers with a nominal thickness of $10\mu\text{m}$. This substrate was fabricated on an oxidized silicon carrier using a conventional polyimide dielectric thin-film multilayer scheme with copper metallization and chromium adhesion layers. An etch barrier layer was placed between the initial polyimide layer and the oxidized carrier surface to allow separation of the thin film substrate from the carrier after assembly. The novelty of the new approach is not only the replacement of the conventional flex substrate with the thin-film multilayer substrate, but also in the module assembly where all the assembly operations are performed prior to substrate release from the carrier. This improvement eliminates the need for a

special vacuum fixture to hold the substrate flat during assembly—thus significantly simplifying and speeding up the operation. The released chip-substrate system is truly flexible and easily conformed to a curved surface, as can be seen in Figure 5.

The initial health or physiological monitoring system is in its design phase. The sensors have been selected and the power and weight budget for the entire system is given in Table 1. It can be seen from Table 1, that with thin rechargeable Lithium polymer batteries producing 50 to 200 mAH (which is currently within the capacity of commercially available thin lithium polymer batteries) the unit can be operative for 12 hours to 50 hours before a recharge would be necessary. This is more than enough time to accommodate a daily exercise routine, a twelve hour bike ride or hiking adventure or even 24 hour to several day heart monitoring activity (using pulse oximetry). In fact, the unit could provide monitoring for several days depending upon the size (thickness) of the polymer battery, the functionality selected and the frequency of transmission events. For example, using thinned electronics coupled with a thicker polymer battery a two credit card thick module could last up to two weeks (before a recharge is necessary) dependent upon monitoring and transmission scenario. The unit is envisioned to have fully selectable or de-selectable sensors and significant on board storage to simplify data transmission requirements.

A key element to the system besides its obvious advantages of size, weight, and functionality (as compared to other known wearable monitoring devices) is its easy attachment and removal from the sensor containing garment. Several techniques of garment attachment have been developed including: a wiring pigtail in a hidden pocket, guided sliding contacts, and an advanced optical interconnect method. Another key factor is the flexibility in read out options. Depending upon the selected mode of readout (wireless or contact) the station for reading and analyzing the data can vary. It can be a base station type where the module is inserted. A connector mounted in the base station engages the sensor contact strip on the card module and sends the command to download the stored on card memory information. If the read out is accomplished remotely via wireless, then the read out and

programming could be done on a computer located in the user's home, a doctors office, or perhaps on the sidelines at a sporting event depending upon the operational scenario. Circuitry has been provided that will uniquely identify and/or serialize each credit card module, thus a central monitoring station could identify which credit-card module is sending the signal.

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Table 1: Sensors and Electronics Power Draw and Weight

<i>Sensor</i>	<i>Power (mA @ 3V)</i>	<i># of Sensors</i>	<i>Sample Time per Sensor (sec)</i>	<i>Sampling Rate (Hz)</i>	<i>Total Power (mAH @ 3V)</i>	<i>Modified Weight (gm)</i>
Temperature	0.65	10	0.15	0.02	0.0163	20
Humidity	1	10	60.0	0.003	2.0000	12
Strain Gauges – Respiration	0.14	4	0.15	1	0.0840	1
Acoustics	0.5	8	0.15	1	2.1600	10
Pulse – Oximeter	33.85	1	10	0.003	1.1283	21
Galvanometer	5	1	1	0.003	0.0014	5
CLOTHING SENSOR SUITE					4.2617	69
Sphygmomanometer	3	1	60	0.1	0.0001	185
Strain Gauges – Movement	0.14	8	0.15	100	60.48	16
OPTIONAL SENSORS		3			60.4801	201
A/D	0.5	4	121	1200	0.6667	1
Microcontroller	0.000022	1	60	60	0.0000	1
Accelerometer	0.18	1	1	60	0.0030	1
Memory	15	1	1	60	0.2500	1
Battery (200mAH)						6-10
ELECTRONICS					0.9197	10-14
Total (W/O Optional Sensors)					5.1814	79-83

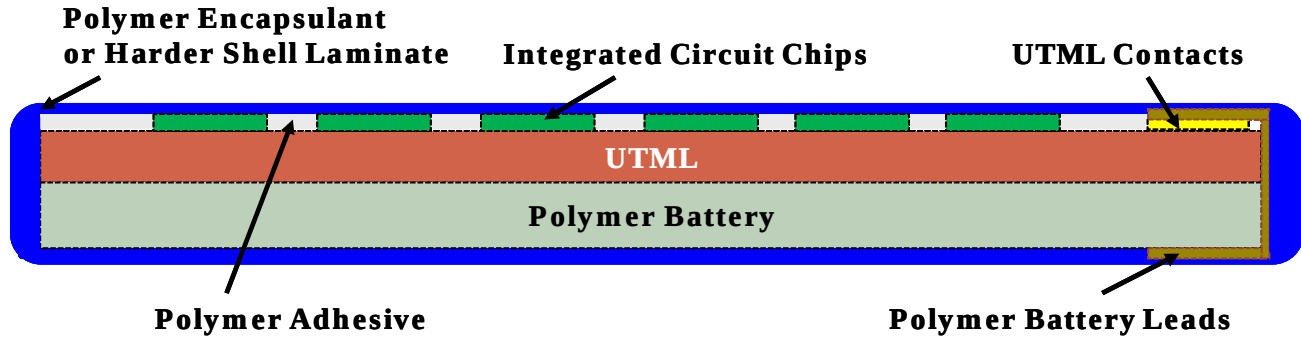


Figure 1: Cross-sectional View of the Electronics Module of the Physiological Monitoring System. UTML stands for ultra-thin multilayer.

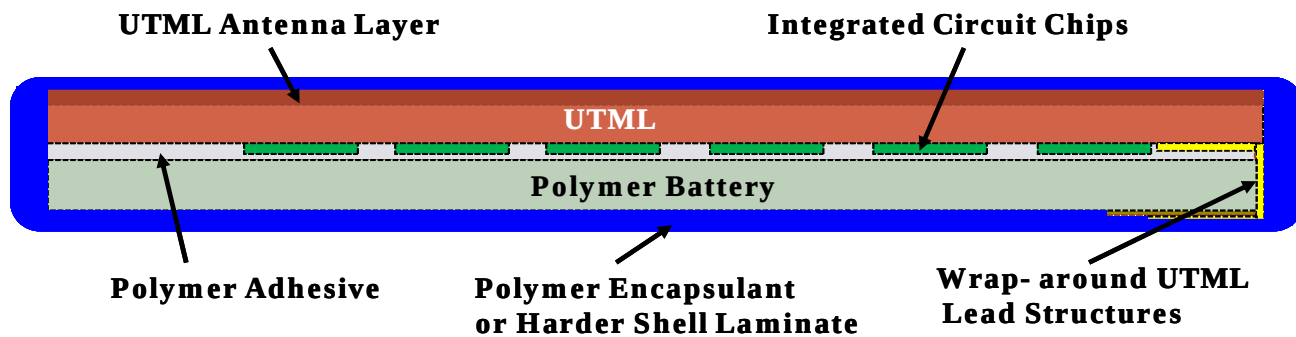


Figure 2: Cross-Sectional Structure of Credit Card Style Physiological Monitoring System with Integral Antenna as part of Ultra-Thin Multi-layer (UTML) Substrate System (antenna in surface position)

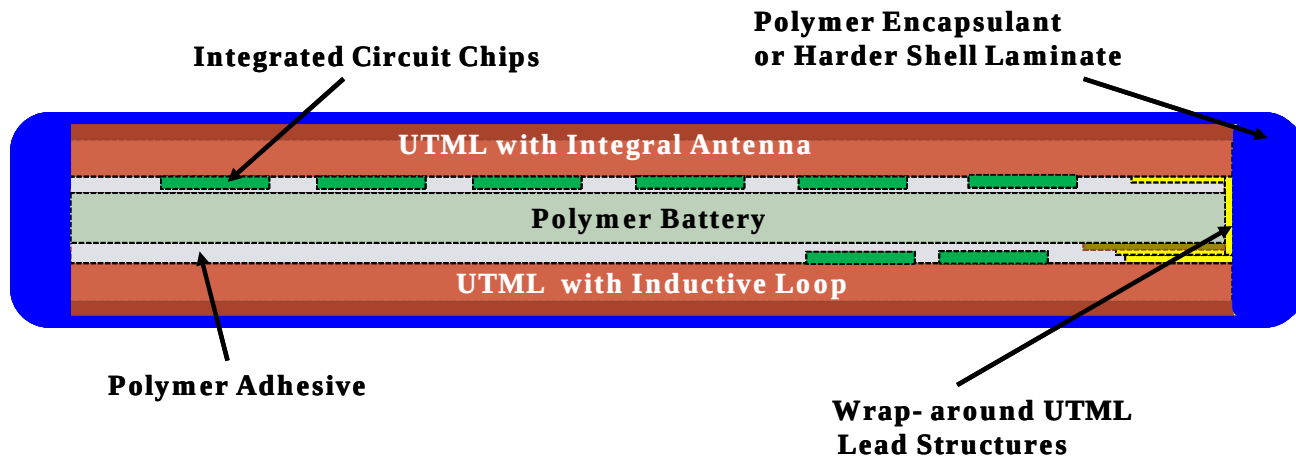


Figure 3: Cross-Sectional Structure of Credit Card Style Physiological Monitoring System with Integral Antenna as part of Ultra-Thin Multi-layer (UTML) Substrate System (antenna in surface position) and a Second UTML containing an inductive loop and battery charging circuitry.

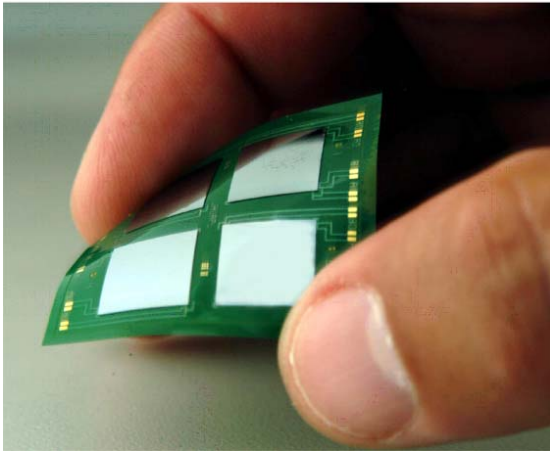


Figure 4: Thinned Microcircuit Test Sample Containing 25-Micrometer Thin Die Mounted on Flex. Overall Thickness is 100 micrometers.

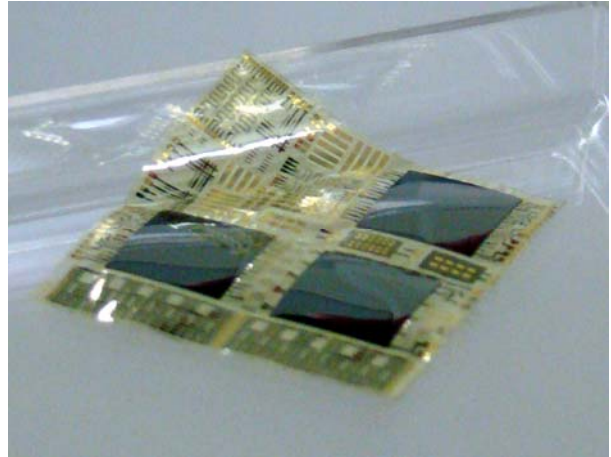


Figure 5: Thinned 25-Micrometer Die on Multilayer Thin Film Substrate Lying against the Curved Surface of a Petri Dish. Substrate Thickness is 10 micrometers. Overall Assembly Thickness is less than 50 micrometers.