Reconfigurable Fabric: An enabling technology for pervasive medical monitoring[1]

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ABSTRACT
In the past few years exciting advances in the development of pervasive computing technologies have taken place, in particular the field of flexible electronics is emerging: electronic components such as transistors and wires can be built on a thin flexible material, and polymer wires can be made to be flexible and durable. These technologies offer the opportunity to weave computation, storage, and communication into the fabric of the very clothing that we wear, thereby creating an intelligent fabric (also called electronic textiles or e-textiles) [1] [2] [3] [4] [5] [6] [7] [8]. The implications of seamlessly integrating a large number of communicating computation and storage resources, mated with sensors and actuators, in close proximity to the human body are quite exciting. This paper presents the motivation for the Reconfigurable Fabric (RFab) project underway at UCLA. Reconfigurability on multiple architectural levels is critical for intelligent fabrics. Because the wires used for communication and energy distribution are woven into the garment, an intelligent garment needs to be able to find new interconnection pathways when the garment is damaged so that operation can continue. In addition, reconfiguration at the link layer can allow the creation of interconnection topologies that are well-suited to performing a particular computation. Reconfigurability is also needed at the system level in order to allow the computational load to be balanced over the available computational units. This paper discusses the system architecture of the RFab-Vest, a pervasive medical monitoring jacket, the design decisions that led to it, and describes the first complete RFab-Vest prototype.

I. INTRODUCTION
The past few years have seen exciting advances in the development of pervasive computing technologies. Computation, storage, and communication are now more or less woven into the fabrics of our society with much of the progress being due to the relentless march of Silicon-based electronics technology as predicted by Moore's Law. The emerging field of flexible electronics, where electronic components such as transistors and wires are built on a thin flexible material, offers a similar opportunity to weave computation, storage, and communication into the fabric of the very clothing that we wear, thereby creating an intelligent fabric (also called electronic textiles or e-textiles) [1]. The implications of seamlessly integrating a large number of communicating computation and storage resources, mated with sensors and actuators, in close proximity to the human body are quite exciting; for example, one can imagine biomedical applications where biometric and ambient sensors are woven into the garment of a patient to trigger and modulate the delivery of a drug. The Reconfigurable Fabric project, a multi-disciplinary effort currently underway at UCLA, aims to develop such an intelligent and pervasive patient monitoring garment.

Realizing such novel applications is not just a matter of developing innovative materials for flexible electronics, along with accompanying sensors and actuators. The characteristics of the flexible electronics technology and the requirements of the applications enabled by it necessitate radical innovation in system-level design. Electronic components built of flexible materials have characteristics and computation-communication cost trade-offs that are very different from that of silicon and PCB-based electronics. Further, the operating scenarios of these systems involve environmental dynamics, physical coupling, resource constraints, infrastructure support, and robustness requirements that are distinct from those faced by traditional systems. This unique combination requires one to go beyond thinking of these systems as traditional electronic systems in a different form factor. Instead, a re-thinking and complete overhaul of the system architecture and the design methodology for all layers of these systems is required.

Paper Overview and Contributions
This paper presents the motivation for the Reconfigurable Fabric project underway at UCLA and describes the development of the first RFab-Vest, a pervasive medical monitoring jacket. After a brief discussion of the overall application scenario of the RFab-Vest, the paper focuses on three distinct aspects of the design of such a vest, which span three different levels of the design hierarchy, namely the technology level, system architecture level, and application level. At the technology level mentioned in section II, we describe the various component blocks that comprise the vest, including a novel flexible polymer temperature sensor that we have fabricated for integration into the RFab-Vest. Next, we discuss how to satisfy the crucial need for fault-tolerance in such a vest through judicious interconnection architecture selection, and system-level fault monitoring and reconfiguration. We describe the various algorithms that we have developed for reconfiguring the interconnection topology of the RFab-

[1] Author names appear in alphabetical order. This paper is based on work funded by the National Science Foundation

Vest in the case of interconnection failures. Finally, at the application level, because the RFab-Vest will be used to monitor the human body, we describe algorithmic techniques for detecting and identifying “angina pectoris”, a potentially fatal heart condition, from electrocardiogram (ECG) signals.

Driver Application

Although the goal of the RFab project is to investigate system architecture and design methodology concepts for electronic textiles, successful systems research of this nature requires that one not only develop these concepts, but also validate them in context of real technology constraints and application requirements. Therefore, we use pervasive patient monitoring and sensor-driven personalized trans-dermal drug delivery as our driver application. One possibility of leveraging electronic textile technology in the context of such an application is to create a flexible garment (i.e., vest) that the patient can wear, which has sensing, computation, communication, and actuation elements embedded in it. We are developing such a prototype vest called the RFab-Vest. Ideally, such a personalized drug delivery vest should have sensors on both the interior (to measure physiological readings) and on the exterior (to measure environmental readings such as the presence of toxins in the surroundings), and a software-controlled, electrically-actuated trans-dermal drug delivery system. It should allow low-latency, fine-grained adaptation of the drug dosage based on continual physiological measurements in the case of patients, and based on both environmental and physiological measurements in the case of people operating in hazardous environments. More generally, our application driver is representative of biomedical applications where information technology is integrated into fabrics and textiles. Figure 1 shows the overall system architecture of the RFab-Vest. As is evident from the Figure 1, the vest consists of four main subsystems: control (or computation), communication, sensing, and actuation. The first prototype of RFab-Vest tested with a bread board is shown in Figure 2.

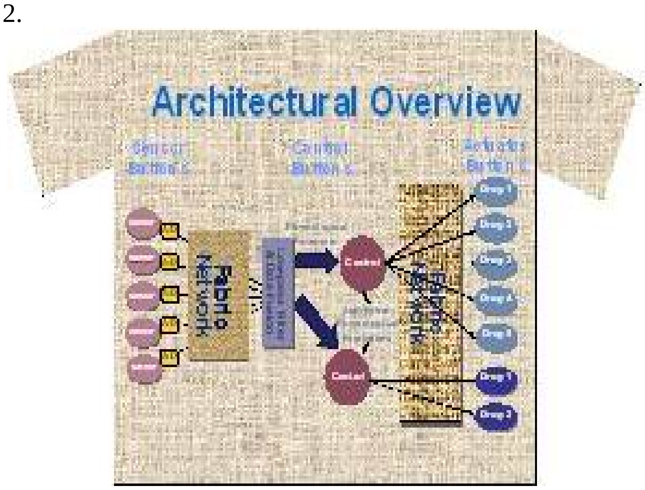

Figure 1. System architecture of the RFab-Vest,

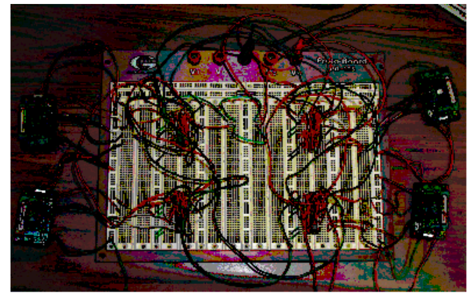

Figure 2. Picture of the completed RFab-Vest prototype

The Need for Fault Tolerance

Since the RFab-Vest will be used for medical, life-critical applications, the single most critical requirement of such a vest is an extremely high level of robustness and fault-tolerance. The vest should properly detect and correct abnormal patient conditions reliably, even if the presence of wear and tear in the system. The most straightforward method of providing resilience to wear and tear is re-configurability. Like any garment there is the potential for damage (e.g. being ripped or spilled upon) as the wearer engages in various activities. For example, if the garment is torn and wires interconnecting computational nodes or sensors are broken then the garment will need to reconfigure its interconnection/communication topology in order to route around the tear.

A smart garment needs to monitor its own system health in order to identify and deal with failures. Two methods of implementing fault tolerance are on-demand and continuous. On-demand fault tolerance attempts to fix a fault only at the time when the fault first inhibits the achievement of a goal. Although on-demand fault tolerance can be simple the drawback is that one will not realize that something is broken until one wants to use it. Only at that point will the garment attempt to fix the fault. If the fault is not repairable, then identifying the fault at precisely the moment when you need to perform a critical task could have disastrous consequences. Although on-demand fault tolerance is suitable for a large class of applications, it is not suitable for medical applications where human life may be at stake. For such critical applications it is important that the garment be ready and waiting to assist the patient. If a fault occurs it should be fixed immediately. If a fault is unfixable the wearer should be notified immediately so that some appropriate action can be taken (replace the garment). Because our target applications for such garments are medical the system needs to be constantly monitoring its own state in order to detect faults in a timely fashion. There are four resources that need to be monitored: computational elements, communication buses, sensors, and batteries. A combination of these four resources will determine whether or not the garment can respond to a patient’s health problem appropriately and in a timely manner. Computational elements are distributed throughout the garment and are responsible for its diagnosis and maintenance. Data buses and sensors are monitored by each node periodically sending out the equivalent of ping messages to neighboring nodes and sensors. Faults are detected when a node notices that it has not heard from another node (or sensor) within some timeout period. When a timeout occurs the network attempts to fix the fault and determine whether the garment is still capable of carrying out its mission. Through such a system level approach to re-configurability, we ensure robust operation of the RFab-Vest.

II. THE TECHNOLOGY: Building the RFab-Vest

For our prototype RFab-Vest we use off-the-shelf parts. For the computational nodes, we use mica2dot mote [9]. To support link-layer reconfigurability we used multiplexer/demultiplexers to create switches. Each mote has control over a switch allowing it to alter its connectivity locally.

Computational Elements

The dot motes developed at the University of California, Berkeley offer a tiny, low cost computation platform for embedded applications. It comprises a programmable ATmega128 microcontroller from Atmel. The ATmega128 [10] is a low-power CMOS 8-bit RISC microcontroller. The ATmega128 achieves a throughput of up to 1 MIPS per MHz. The ATmega128 also provides 128K bytes of In-System Programmable Flash, 4K bytes of EEPROM, 4K bytes of SRAM, and several peripherals including a real time counter, four timers, two USARTs, an ADC, and a byte oriented Two-wire Serial Interface -- also called the Inter Integrated Circuit (I2C) [11] interface.

The dot motes are connected to two I2C buses through programmable switches to create the distributed computation fabric drawn in Figure 3. The switches used for this purpose were the SN74LV4052A ICs from Texas Instruments. These dual 4-channel CMOS analog multiplexers/demultiplexers are designed for 2-V to 5.5-V VCC operation and are bidirectional in functionality.

Topology and Switches

For our initial topology we chose to arrange four motes in a square pattern and interconnect them as shown in Figure 3. To provide fault tolerance at the link layer we provide redundant interconnects between nodes. In our design, although there are multiple interconnects, each node is only able to connect to one horizontal bus and one vertical bus at any point in time. Reconfigurability at the link layer is provided by allowing nodes to choose which vertical-horizontal bus pair to connect to. Each mote controls two 4-channel analog multiplexers/demultiplexers (mux/demux). These two mux/demux form a switch which enables a mote to connect a vertical I2C to a horizontal bus as shown in Figure 3. Currently we are investigating a topology of four motes connected through vertical and horizontal buses shown in Figure 3. A picture of switches designed for this purpose along with dot-motes is presented in Figure 4.

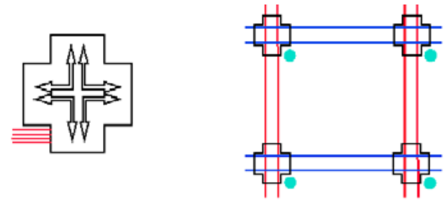

Figure 3. (left) crossbar architecture, (right) four motes and switches arranged in a square

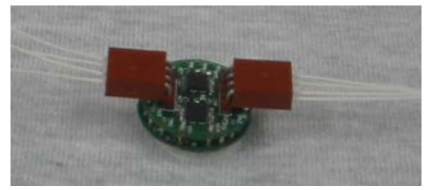

Figure 4. A dot-mote along with a switch

Sensing Components

Myocardial Ischemia is basically caused by lack of oxygen and nutrients to the contractile cells. Frequently it may lead to myocardial infraction. This causes severe consequence of heart failures or arrhythmia that may yield death. An electrocardiogram (ECG / EKG) is an electrical recording device of the heart signals and is used in the investigation of heart diseases including Ischemia. The ECG monitoring system, that we use, utilizes ten electrodes and collect samples periodically. Digitized samples are sent to a dot-mote for Ischemia detection process through serial communication protocol. The ECG that we utilize is manufactured by Midmark Diagnostics Group.

The other sensing component that we have developed but have not added to the RFab-Vest yet is the temperature sensors. Plastic electronic offers great opportunities in the area of flexible electronics, which will be embedded into the RFab-Vest. To demonstrate this feasibility, we give an example of applying this technology to make a flexible sensor that can monitor body temperature. It has been shown that a heterogeneous p-n junction polymer photovoltaic device can behave as a good photo detector under reverse bias [12]. The photosensitivity of polymer diodes is comparable to that of inorganic photodiodes [12]. About 0.2 A/W in the visible range can be achieved by a simple ITO/MEH-PPV:C60/Ca photodiode at –10V bias. (MEH-PPV and C60 are p-type and n-type organic semiconductors, respectively). We plan to use this supreme photosensitivity of a polymer photodiode combined with a thermo chromic material to fabricate a flexible temperature sensor that can be easily applied in large-area temperature detection. The device structure is shown in Figure 5. The device consists of a thermo chromic film sandwiched between a polymer light-emitting diode (PLED) and a polymer photodiode. The absorption of the thermo chromic film depends on its temperature; therefore the number of photons absorbed by the film is modulated according to the surrounding temperature. The polymer photo detector has maximum sensitivity to green light, so a green PLED with a maximum emission wavelength of around 510 nm is used as a light source. The highly sensitive polymer photodiode acts as the detector, which is fabricated with the

ITO/PEDOT/MEHPPV:PCMB/Ca/Al structure (PCBM is a derivative of C60). The operation of the sensor is described as follows. The green PLED was biased at a constant current of 5mA and the photo detector was biased at –3V. At 25 ºC, the thermo chromic film is opaque and very little light can pass through it to reach the photodiode. Consequently, the photocurrent is small. At higher temperature, the thermo chromic film becomes transparent and more light from the PLED can pass through the film, resulting in a much higher photocurrent. Hence, the higher photocurrent is an indication of higher temperature.

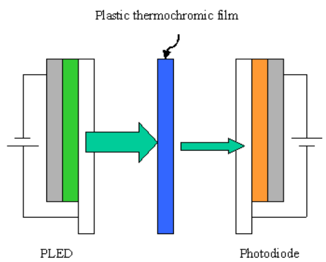

Figure 5. The device structure of a polymer temperature sensor

Interconnection Materials

For interconnection purposes, we will use organic conducting materials to serve as a large and flexible backplane to integrate wiring and switches. Among conducting organic materials, conducting polymers (CPs) are better choices than traditional conducting materials, such as copper, for the fabrication of the RFab-Vest in several respects. First, the weight of CPs is much less than metals, so a vest integrated with polymer materials rather than metal wires would be much lighter in weight. Second, polymers potentially have better mechanical properties as compared to metals when used as fibers. For example, plastics usually have higher tensile strength, which is required for clothes to stretch. A garment made from such plastic fibers would then be able to withstand higher stress before failure. This unique property is of particular importance, since much higher mechanical stress may be encountered in the RFab-Vest, which is unlike the application of conducting materials in the traditional electronic industry, where the materials usually are not subject to dynamic stress. Finally, because of the flexibility, fabrics made of conducting polymers are more comfortable.

The ideal material with the mentioned properties is probably a mixture of highly conducting polymer, such as highly doped polyethylene or polythiophene, and a traditional textile with high tensile strength, such as nylon or polyester. It has been reported that the surface resistance of fabrics coated with conducting polymer is as low as 10 (ohms/square), which is several orders lower than those of carbon-filled fibers or fabrics blended with carbon or steel [13]. However, in the first prototype of RFab, we employed conducting fibers manufactured by Dupont® called ARACON® since development of conducting polymers is still in a premature stage at UCLA. Another study has investigated the electrical performance of metal fibers integrated into the textile [14].

III. ACHIEVING SYSTEM LEVEL FAULT TOLERANCE THROUGH INTERCONNECT RECONFIGURABILITY

Because the RFab-Vest is meant to allow its wearer mobility while being monitored the algorithms running on the vest need to be power efficient. In addition, these algorithms must be tolerant to node failure and interconnection failure. Lastly, the algorithms must be able to satisfy timing constraints. For example, if a patient begins to have a heart attack it is crucial that the RFab-Vest administer drugs in a timely manner.

Interconnection Reconfiguration Algorithm

The motes communicate with each other using an I2C bus as a broadcast medium. The interconnection reconfiguration algorithm needs to maintain a broadcast medium in the face of link failures. The general idea of the algorithm is that the nodes collect connectivity information by sending ping messages to each other periodically. When a node notices that it has not received a response from one or more nodes within some timeout period the node attempts to reconfigure its local switch to regain connectivity. Because a node has a map of the interconnect topology (based on the results of sending ping messages) it can determine how the network has been partitioned. In our preliminary study there are only four nodes. Therefore, the only partitions possible are horizontal, vertical, or a corner partitions. In the case of a horizontal (vertical) partition there are two groups of two nodes. Because a node’s horizontal and vertical connectivity are independent is able to change its horizontal connectivity without affecting its vertical connectivity (and vice versa) when a node detects a horizontal (vertical) partition it only changes its vertical (horizontal) connectivity bus. In the case of a corner partition, a single node is partitioned from the other three. The single node must change both its horizontal and vertical data bus. In the three node partition, only the two adjacent nodes can affect the connectivity.

As discussed in Section I, a broadcast algorithm is designed to check the connectivity of the network periodically. In case of a partition, a token is generated to circulate among the portioned nodes. After some predefined time, when no response is received from one or more motes, the mote which has the token sends a halt message to all the motes on the I2C bus and will attempt to fix the topology based on the algorithm described before. Upon receiving the halt message, all the other motes initiate to fix the topology as well. When fixing topology is finished, they all go into the halt mote. The master mote wakes all the motes up by broadcasting a wake up message once it observes that the network is fixed and connected again.

In our implementation, each node is connected to two horizontal and two vertical buses. Therefore, a maximum of five faults can be sustained while maintaining connectivity. The minimum number of failures required for a network partition is four.

IV. EXPERIMENTAL RESULTS

We performed several experiments to measure the reconfigurability and fault tolerance of the RFab-Vest prototype. The experiments were performed using the four dot-motes topology shown in Figure 3. A picture of RFab-Vest is shown in Figure 6. Each dot mote controls a switch logic that is capable of connecting various combinations of the two horizontal and vertical buses passing through it.

A primary design goal of the RFab-Vest is to be reliable and fault tolerant in the presence of wire failures (i.e., breaks). We have designed a reconfiguration mechanism to increase the degree of fault tolerance of the RFab-Vest. However, RFab-Vest is designed for medical monitoring applications and under certain circumstances, the patient might need immediate treatment, hence, the reconfiguration time becomes a critical measure. In our reconfiguration algorithm, to monitor that the system is functioning, a token is circulated among the motes and once each mote receives the token, it broadcasts it's presence to all the other motes. So the token cycle time plays an important role in how fast the fault detection and reconfiguration is performed. For all our measurements the mote's internal timers generate 15.3 interrupts per second. Faults are created manually by disconnecting I2C buses. The token cycle time as well the (worst case) cost of recognizing/correcting various faults are presented in Table 1. As can be seen from the table, the RFab-Vest is able to detect faults quickly and reconfigure itself to maintain correct system functionality, thereby achieving the desired goal of system-level fault tolerance.

Task	Time (sec)
Token Cycle Time (worst case)	0.25
To detect a fault in the vertical/horizontal partitioned network (worst case)	0.55
To detect a fault in the corner partitioned network (worst case)	0.70
To reconfigure the network (worst case)	1.1

Table 1. Reconfiguration Time

Figure 6. RFab-Vest

V. APPLICATION LEVEL CASE STUDY: Heart Attack Detection and Drug Delivery System

One of target applications of RFab-Vest is the detection of possibly fatal heart problems, specifically unstable angina pectoris. Angina Pectoris is a fatal medical condition with more than 7 million sufferers in the U.S. alone. In the unstable angina pectoris form of the condition, fatal attacks happen in an unpredictable manner, even when the patient is at rest. Using the architecture that has been discussed in the previous sections, we can achieve constant monitoring and life-saving drug delivery in the emergency situation even when the patient is away from any conventional emergency medical help. With the RFab-Vest the patient can have a personalized tuning for the system by his/her physician and can continue with the normal life activities with the vest. Drug delivery algorithms running on the vest, finely tuned by the patients physician, can be used prevent any fatal results.

Angina pectoris is characterized as an acute chest pain or discomfort due to coronary heart disease and is considered as a symptom of myocardial ischemia. Electrocardiogram analysis is the standard used for the diagnosis of ischemia. However, ECG waves are highly patient dependent and the analysis is generally performed by the clinician manually (through observation of the ECG waves).

Ischemia Detection and Drug Delivery Method (IDDD):

Our ischemia detection algorithm incorporates a collection of initial tuning sessions to extract the normal heart pattern of the patient. These initial ECGs are selected to include a range that span different activity levels and various days of the initial tuning period (rest, exercise, stress...etc). For diagnosis, common ECG patterns of the heart signal are used such as: heart rate, PR interval, QRS duration, QT interval duration, ST interval…etc. In addition, a collection of abnormal ECG patterns associated with the ischemic conditions are stored. Normal ECG patterns of the patient along with the standard indications and abnormal patterns of ischemia are incorporated as a basis for the rest of the automated analysis that is performed by the reconfigurable vest as shown in Figure 7. At the end of the initial tuning period, the drug delivery decision is based upon tuning information provided by the patient’s cardiologist. Tuning of the algorithm will determine the criticality of the wave according to the deviation from the normal values of the patient and the matching with abnormal ischemic patterns according to the guideline provided by the clinician through tuning.

Nitroglycerin delivery through a patch is used as an initial response to heart attack. Nitroglycerin causes tension to be released in the heart muscles and the arteries, enhancing blood flow in the heart. One of the main reasons that nitroglycerin is used in this system is the fact that it does not generate any risk to the patient if the condition is not actually a heart attack. Currently we have developed an initial version of the IDDD algorithm. At this level the algorithm tracks basic values in the ECG signal: Heart Rate, PR Interval, QRS Duration, QT Interval, slope of the ST Interval, along with the basic voltage values of the signal on the corresponding ECG lead. For the initial version of the algorithm we focused on ST region analysis as one of the main indications of ischemia. Ischemia has common indications such as: lack or inversion of T region in the ECG signal, deviation in the elevation and slope of the ST interval.

Below are some sample runs of the current version of the Ischemia Detection and Drug Delivery Algorithm on sample

ECG voltage points. The given ECG voltage values are sampled to 200 samples per analysis window and the heart signal is analyzed based on the following average ranges for the patient for the specific probe averages for the analyzed patient: Heart Rate: 60-100 beats per minute, PR interval:0.12-0.20 sec, QRS duration:0.06-0.10 sec, QT interval:<0.40 sec, VR: 5 - 7mV, VP: 1.5 – 2.5 mV, VQ: (-0.5)-(-1) mV, VS : (-0.5)-(-1) mV, VT: 1.5- 2.5mV. In the example runs of a hypothetical average patient X, ischemic and abnormal heart signals are detected. In the ischemic ECG, the ST region of the curve has values abnormally lower or non-existing compared to patients average heart signal shown in Figure 8. Similarly an abnormal heart signal detected with unusual QRS complex with extremely low 1mV R voltage on the specific probe of the ECG as shown in Figure 9.

At this stage of implementation our ischemia detection algorithm is capable of detecting ischemic heart attacks that show ST region indications such as: non-existing ST region, elevation, slope abnormalities according to the preset normal and abnormal ranges. Furthermore, the algorithm is capable of detecting other heart signal abnormalities such as QRS complex width, abnormal interval ranges and voltages for P,R,S,T,Q waves, etc. As a crucial part of its nature the algorithm is fast and runs on real-time data.

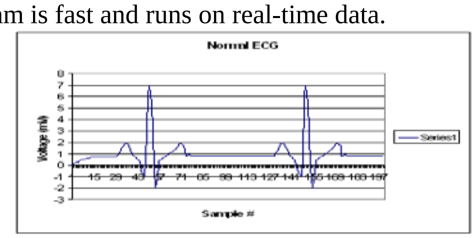

Figure 7. Normal ECG signal

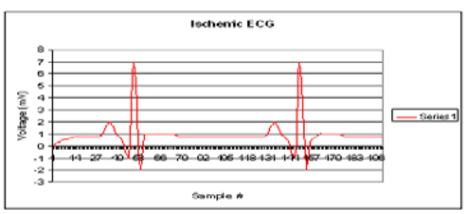

Figure 8. Ischemic heart signal detected by the IDDD algorithm, unusually low or non-existing ST slope

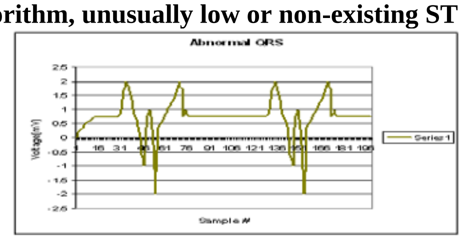

Figure 9. Abnormal QRS complex detected by the IDDD algorithm with abnormal voltage value for R wave

VI. CONCLUSION AND FUTURE WORKS

The Reconfigurable Fabric project at UCLA promises to make advances in sensors, materials, and system architecture for intelligent garments. In the future we plan to expand our prototype, creating larger topologies, and updating our link reconfiguration algorithm for use in larger topologies. In addition, we plan to work on scheduling algorithms for the RFab-Vest to both minimize power consumption as well as to meet deadlines that are imposed by medical applications. We also plan to integrate an ECG heart monitor and transdermal drug delivery system into our prototype. Lastly, we will integrate the system into a wearable garment (a vest), using a flexible substrate as well as polymer fibers.

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