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(71) Applicant *(for all designated States except US)*: **AWARE TECHNOLOGIES, INC.** [US/US]; 338 Conant Road, Weston, MA 02493 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **DEVAUL, Richard, W.** [US/US]; c/o Aware Technologies, Inc., 338 Conant Road, Weston, MA 02493 (US). **BARKALOW, Daniel** [US/US]; c/o Aware Technologies, Inc., 338 Conant Road, Weston, MA 02493 (US). **CARLTON-FOSS, John** [US/US]; c/o Aware Technologies, Inc., 338 Conant Road, Weston, MA 02493 (US). **ELLEDGE, Christopher** [US/US]; c/o Aware Technologies, Inc., 338 Conant Road, Weston, MA 02493 (US).

(74) Agents: **KUTA, Christine, M.** et al.; Bergman Kuta LLP, P.O. Box 400167, Cambridge, MA 02140 (US).

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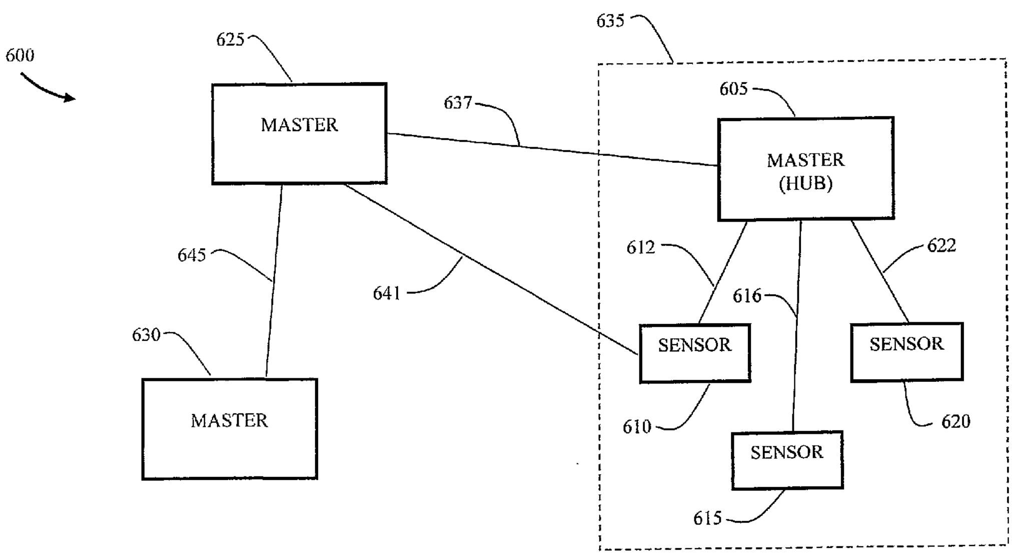
(54) Title: METHOD AND SYSTEM FOR EXTENDED WEARABLE PERSONAL AREA DATA NETWORK



(57) Abstract: A remote monitoring system includes an on-body network of sensors and at least one analysis device controlled by a hub. The sensors monitor human physiology, activity and environmental conditions. The monitoring system includes a data classifier to take sensor input to determine a condition fo the person wearing the remote monitoring system. The remote monitoring system is further able to determine a level of confidence in the determined condition.

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METHOD AND SYSTEM FOR EXTENDED WEARABLE PERSONAL AREA DATA NETWORK

BACKGROUND

Many people, such as soldiers, police, fire fighters, rescue workers, etc., work under hazardous and life-threatening conditions. Many other people are at increased risk of injury or death as the result of a chronic health condition, or complications resulting from the treatment of acute illness, disability, or advancing age. Other people suffer from chronic, or at least sustained, conditions that require long-term monitoring and treatment. People in all of these circumstances may benefit from continuous monitoring, automatic real-time analysis, and proactive reporting of important changes in their health, physiology, activity state, or environmental conditions. Furthermore, those who are responsible for diagnosing, caring for, rescuing, treating, or developing medications for such individuals may also benefit significantly from such monitoring by allowing more timely, less risky, and less expensive interventions.

For example, soldiers, fire fighters, rescue workers, and many other first-responders work under hazardous conditions. These individuals could benefit greatly from advance warning of hazardous environmental conditions, fatigue, illness, or other problems. Such information could allow for improved performance, the avoidance of injury or death, and the timely notification of individuals, team members, and rescue workers in the event that unusual hazards are detected or intervention is needed. Furthermore, in situations where intervention resources are limited or rescue is difficult or dangerous, this information could be invaluable for risk management and triage, allowing individuals in the field, team-members, and rescue workers to make better decisions about such matters as the deployment of human resources. By providing individuals, team-members, and rescuers with salient, timely information, everyone involved benefits from improved situation awareness and risk management.

Likewise, for those suffering from acute or chronic illness, or for those who are at elevated risk for illness or injury, the timely detection and automated reporting of life-threatening injury, disease onset, or medical complication could mean the difference between life and death. Even more valuable than the automatic detection of a crisis may be the reporting of danger signs or leading indicators that may allow a crisis to be avoided all together.

Humans respond differently to different conditions. For example, stressors such as heat and dehydration become critical at different levels for different people. Further, a person with heart disease has a different cardiovascular response that a person with heart disease. In short, people respond somewhat differently to stimuli and stressors than other people. An effective monitoring system would take this into account.

Information relevant to attempts to address these problems includes work at the U.S. Army Research Institute of Environmental Medicine (USARIEM), a part of Natick Laboratories of the United States Army. The USARIEM discloses a hand-sized monitor that miniaturizes Bruel and Kjaer instruments for measuring wet bulb and dry bulb temperature that have transformed heat risk assessment. Data from this monitor is translated to an algebraically calculated estimate of risk from heat stress for lowered productivity or work stoppage and heat prostration. This device is not based on any individual's data. That is, the device assumes that all people are the same. The device is a local monitor, lacking the proactive remote notification features.

Another device in the conventional art is the hand-held doctor project of Richard DeVaul and Vadim Gerasimov of the MIT Media Lab. The hand-held doctor includes a device having sensors for temperature, heart beating and breathing to be used to monitor a child's body. The hand-held doctor further includes infra-red connectivity to a robot which performed actions that reflected the measurements. The first and only prototype of the hand-held doctor system included a small personal Internet communicator-based (i.e., PIC-based) computer with analog-to-digital converters and a radio frequency transmitter, three hand-built sensors, a robot with a receiver, and a software program. The sensors included a thermosensor to measure body temperature, a thermistor-based breathing sensor, and an IR reflectance detector to check the pulse.

Also developed at the MIT Media Lab, the "Hoarder Board," designed by Vadim Gerasimov, had the purpose of collecting large amounts of sensor data. The board can be configured and programmed for a range of data acquisition tasks. For example, the board can record sound with a microphone add-on board or measure electrocardiographic data, breathing, and skin conductivity with a biometric daughter board. The board can use a CompactFlash device to store sensor information, a two-way radio modem or a serial port to communicate to a computer in real time, and a connector to work in a wearable computer network. When combined with a biometric daughter board or multi-sensor board, the system is capable of physiology monitoring or activity monitoring with local (on-device) data storage. The board also supported a simple low-bandwidth point-to-point radio link, and could act as a telemonitor. The board has a small amount of processing power provided by a single PIC microcontroller and a relatively high overhead of managing the radio and sensors.

Further conventional art includes products of BodyMedia Co. of Pittsburgh, Pennsylvania. BodyMedia provides wearable health-monitoring systems for a variety of health and fitness applications. The core of the BodyMedia wearable is a sensing, recording, and analysis device worn on the upper arm. This device measures several physiological signals (including heart rate, skin temperature, skin conductivity, and physical activity) and records this information for later analysis or broadcasts it over a short-range wireless link. The BodyMedia wearable is designed to be used in conjunction with a server running the BodyMedia analysis software, which is provided in researcher and end-user configurations, and in an additional configuration that has been customized for health-club use.

Other conventional wearable remote monitoring systems include alert systems that set off an alert when a condition exceeding a selected threshold is detected. One example of such a system is the Personal Alert Safety System (PASS) worn by firefighters.

Further conventional art includes products from Polar Electro Oy of Finland. A heart monitor system from Polar Electro includes a simple rubber strap that holds a heart monitor sensor device on the body of a person. The strap is approximately one inch in width and ¼ inch in thickness.

Still further conventional art includes the Lifeshirt from VivoMetrics, Inc of Ventura, California. The Lifeshirt is an elastic garment including a plurality of sensor. The elastic garment is made to be worn like an undershirt. The Lifeshirt includes wiring used to transmit signals from each of the plurality of sensors to a single receiving device.

It remains desirable to have a method and apparatus for wearable monitoring with real-time classification of data.

SUMMARY

The problems of monitoring individual comfortably, accurately and with the ability to generate notification of hazardous conditions with a level of confidence are solved by the present invention of a wearable monitor including real-time analysis.

Although the wearable component of the Media Lab device (the hand-held doctor) provides physiological telemonitoring capabilities (it streams raw, uninterpreted physiology data over an infrared wireless communications system) it lacks real-time analysis capabilities and accordingly does not provide proactive communications features.

The Hoarder board has a small amount of processing power and accordingly lacks real-time analysis capabilities. For example, the Hoarder board also does not provide proactive communications.

Although the BodyMedia wearable system is capable of real-time telemonitoring and at least some remote real-time analysis, the system continuously captures or wirelessly streams data in real-time to a remote location where analysis can be done.

In contrast, the present inventive technology is specifically designed for the real-time, continuous analysis of data (which may, in some embodiments of the invention, be recorded), and to proactively relay this information and analysis when dangerous or exceptional circumstances are detected. The advances of the present inventive technology include managing power consumption and communications bandwidth.

Further, those conventional systems including an alert system typically operate using simple threshold values which make them somewhat dysfunctional under real world conditions. Whether or not a hazard actually exists is often determinable only by combinations of factors and conditions. Alert systems using simple threshold values often misinterpret the data input. The Personal Alert Safety System (PASS) alarms used by firefighters are a good example of one such dysfunctional alert system. PASS alarms create a considerable nuisance with their false positive responses, and firefighters are therefore inclined to disengage them or ignore them. The problems associated with false positives may in some cases be mitigated by bringing the wearers into the interaction loop by means such as giving them the opportunity to cancel an automatically triggered call for help. This, however, only transfers the burden from one set of individuals (the rescuers) to another (the wearers). While this may reduce the economic cost of false positives it may also place an unacceptable cognitive burden on the wearer.

The heart monitor system from Polar Electro Oy is an incomplete solution for wearable sensors. The chest strap has no positioning functionality. It is up to the user to locate the sensor properly on the body. Further, the Polar heart monitor system has no provisions for holding or for locating a plurality of sensors.

The Lifeshirt from VivoMetrics, Inc. is burdensome to the user. The shirt is uncomfortably tight and overly restrictive for most applications. The fit of the Lifeshirt is not adjustable nor is the sensor placement on the shirt. For example, the Lifeshirt is sometimes acceptable in medical contexts where the information obtained is more important than any patient discomfort and where elaborate readings are taken over time and where medical personnel are available to adjust, monitor and remove the Lifeshirt from the test subject. The Lifeshirt is typically not appropriate in contexts in which users' performance is important, for example, fire fighters, police, air force pilots, naval personnel, or army warriors. The Lifeshirt is generally not acceptable also for athletic applications.

The present invention relates to the use of body-worn or implanted sensors, microelectronics, embedded processors running statistical analysis and classification techniques, and digital communications networks for the remote monitoring of human physiology, activity, and environmental conditions; including vital-signs monitoring; tracking the progress of a chronic or acute ailment; monitoring exertion; body motions including gait and tremor, and performance; detecting injury or fatigue; detecting environmental conditions such as the buildup of toxic gas or increasing external temperature; the detection of exposure to toxic chemicals, radiation, poisons or biological pathogens; and/or the automated detection, real-time classification, and remote communication of any other important and meaningful change in human physiology, activity, or environmental condition that may require notification, treatment, or intervention.

All of these monitoring, interpretation, and proactive communications applications have at their foundation a combination of sensing, real-time statistical analysis, and wireless communications technology. Furthermore, this technology is packaged in a manner that is as comfortable and non-invasive as possible, and puts little additional physical or cognitive burden on the user. It is robust and reliable, unobtrusive, accurate, and trustworthy. It is as simple as possible to operate, and very difficult to break.

A preferred embodiment of the present invention is a wearable system including one or more small, light-weight electronics/battery/radio packages that are designed to be integrated into the wearer's current uniform, equipment, or clothing. These may be packaged as separate, special-purpose devices, integrated into existing gear (watches, cell phones, boots or equipment harnesses, pagers, hand-held radios, etc.), or incorporated directly into clothing or protective gear.

Another embodiment of the invention includes sensors located in readily adjustable clothing, easily adjustable, for example, by the user. In a first arrangement, sensors are located on straps incorporated into a jacket. In a second arrangement, cords are used to adjust the fit of the jacket and placement of the sensors. In a third arrangement, inflatable padding pushes sensors into place on the body of the wearer. In a fourth arrangement, the jacket wraps around the user in a manner that allows the user to readily set the snugness of the fit and maintains the sensors in proper position in contact with the user's body.

<u>Sensor Hub</u>

The center of the wearable system is a sensor hub. If the wearable is monolithic, the sensor hub is a package containing all sensors, sensor analysis hardware, an appropriate power source, and an appropriate wireless communications system to proactively contact interested third parties. The sensor hub package also supports whatever wearer-interaction capabilities are required for the application (screen, buttons, microphone/speaker, etc.) For some applications, a distributed, multi-package design is more appropriate. In these cases, there is a distinguished sensor hub responsible for communicating relevant information off-body, but some or all of the sensing, analysis, and interaction is done in separate packages, each of which is connected to the central package through an appropriate personal area network (PAN) technology.

Personal Area Network

For the distributed wearable configuration, the on-body components are tied together through a personal area network. This network can range from an ad-hoc collection of sensor-specific wired or wireless connections to a single homogeneous wired or wireless network capable of supporting more general-purpose digital communications. For example, a particular wearable application may require sensors or electrodes to be placed against the wearer's skin, woven into a garment, or otherwise displaced from the sensor hub's package. In these cases, the sensors, particularly if they are simple analog sensors, are tied to the sensor hub through dedicated wired connections. In another application, for power consumption or standoff detection reasons, several digital sensing or interaction components are tied together with an on-body wired digital personal area network. In other cases, human factors or other usability constraints may make wired connections between some on-body components infeasible; in these cases, an embodiment of the present invention includes a wireless digital personal area network (RF, near-field, IR, etc.) used to tie some or all of the sensing or interaction modules to the sensor hub. Finally, further alternative embodiments of the present invention combine all three of these personal area networking strategies. In the cases where a wireless personal area network is used, all on-body modules participating in the network have an appropriate network transceiver and power source.

In a further alternative embodiment of the invention, an extended personal area data network includes a plurality of master devices receiving communications from slave devices. In one embodiment, the star topology of the wearable personal area data network described above is extended with multi-master and master-to-master communications links.

Sensor/Analysis Packages

In the case of a distributed, multi-package sensor design, separate packages containing sensors and sensor analysis hardware are distributed about the body as appropriate for the application and usage model. In some embodiments, these packages are analog sensors or electrodes, in which case the "package" is composed of the sensor or contact itself with any necessary protective packaging, appropriately positioned on the wearer's body or incorporated into clothing. In other embodiments, the sensor is a self-powered device with a special-purpose wireless network. In these cases the sensor package includes not only the sensor, but an appropriate transceiver, which in most cases will require a separate power supply. There are completely passive wireless sensors and radio frequency identification (RFID) systems that do not require a power supply, but instead are "powered" through the communications link. In order to conserve power and personal area network bandwidth, some versions of the inventive art will have sensor/analysis packages that combine real-time analysis hardware with the sensor in single package. This version is particularly appropriate for wireless personal area networks in which the cost-per-bit of transmitting data is significantly higher than the cost-per-bit of processing and analyzing sensor data, or in which the available wireless personal area network (WPAN) bandwidth is low. By shifting some of the processing of sensor data away from the sensor hub, lower-bandwidth "summary" or analysis data rather than raw sensor data is sent over the WPAN, thus conserving power and bandwidth.

Wearer Interaction Packages

Some embodiments include user interaction. One or more dedicated user interaction packages are thus included as part of the wearable system to improve usability. Such embodiments may include components as a screen, buttons, microphone, speaker, vibrating motor with the sensor hub or some other sensing/analysis package with an appropriately capable PAN to link it with other parts of the system. For example, in one embodiment, a display is integrated into eyeglasses, safety glasses, or an existing body-worn equipment monitor. Likewise, in another embodiment, an audio alert or interaction system is incorporated into a currently worn body-worn audio communications stem, such as a cell-phone or two-way radio. Other components and arrangements for wearer interaction are possible within the scope of the present invention. The present invention is not limited to those listed here. For example, wearer interaction can also be accomplished by writing new software or firmware modules to enable existing devices to operate with the wearable of the present invention in novel ways. Such devices include cell phones, PDAs, or other currently worn gear that support a wired or wireless communications link with the wearable sensor hub.

Packaging Considerations

One embodiment of the present invention combines a "hard" sensor hub module packaged in an ABS plastic enclosure, and one or more "soft" physiology sensing components that are in direct contact with the skin. Extra care and consideration is taken with these "soft" sensor packages that interact directly with the body. The compatibility of these sensors and their packaging is considered in view of the wearer's activities and other gear and in view of the level of distraction to the user. Improvements in the wearability are achieved when allowable and feasible by minimizing the number of "soft" sensor packages required, and by weaving sensors directly into the fabric of an undershirt, for example, or other existing clothing component.

It is important that the technology described herein is intended for long-term use, and that there is a large difference between designing for short-term wearability and long-term wearability. Many design choices that are acceptable for short-term wearability (and are found in existing biomedical sensing devices) are not acceptable for longer-term use. One example is the temporary use of adhesive electrodes for electro-cardiogram (ECG) or other bioelectrical measurement are acceptable to users, but are not well tolerated for longer-term use, such as envisioned by the technology described here. For long-term wearability, adhesive connections to the skin, prolonged contact with nickel steel or other toxic or allergenic materials, and numerous other potentially slightly irritating or uncomfortable materials or configurations are preferably avoided. Another example of a configuration preferable avoided is the temporary use of a highly constraining and somewhat rigidified under-shirt that holds sensors close to the body at the cost of distraction and the inability to move normally. Instead, as discussed above, sensors are ideally woven into normal attire.

The size, weight, and positioning of the "hard" components is a consideration for wearability and usability. Reducing size and weight as much as possible is important, but robustness and compatibility with an appropriate range of activities and existing gear is also important. Positioning hard components on the body is an important factor effecting comfort, especially for wearers who are otherwise encumbered. Wired connections on the body and the mechanical connections associated with them present certain reliability and robustness challenges. They also present challenges in wearability and usability. In applications using the technology described herein, various embodiments include strain relief to protect the cables and wired connections. Frequently made or broken mechanical connections are designed for extreme durability. At the same time, heavy or bulky connectors – which may be required for applications involving gloved users –are selected to minimize the impact on wearability. For these reasons, it is desirable to minimize the number of wired connections and mechanical interfaces for body-worn applications.

The present invention together with the above and other advantages may best be understood from the following detailed description of the embodiments of the invention illustrated in the drawings, wherein:

DRAWINGS

Figure 1 is a picture of a chest strap according to principles of the invention;

Figure 2 is a picture of a chest strap including wires to a hub according to principles of the invention;

Figure 3 is a block diagram of a first configuration of the hub and sensor placement on a representative human figure according to principles of the invention;

Figure 4 is a block diagram of a second configuration of the hub and sensor placement on a representative human figure according to principles of the invention;

Figure 5 is a block diagram of a hub and sensor network according to principles of the invention;

Figure 6A is a schematic diagram of a first portion of a first hub according to principles of the invention;

Figure 6B is a schematic diagram of a second portion of the first hub according to principles of the invention;

Figure 6C is a schematic diagram of a third portion of the first hub according to principles of the invention;

Figure 6D is a schematic diagram of a fourth portion of the first hub according to principles of the invention;

Figure 7A is a schematic diagram of a first portion of a second hub according to principles of the invention;

Figure 7B is a schematic diagram of a second portion of the second hub according to principles of the invention;

Figure 7C is a schematic diagram of a third portion of the second hub according to principles of the invention;

Figure 7D is a schematic diagram of a fourth portion of the second hub according to principles of the invention;

Figure 8 is a flow chart of the statistical classification process according to principles of the invention;

Figure 9 is a flow chart of the process of the classifier module according to one embodiment of the invention;

Figure 10 is a diagram of a representational human figure wearing a jacket including a sensor strap according to one embodiment of the invention;

Figure 11 is a diagram of the jacket of Figure 10 including strap adjustment features according to one embodiment of the invention; and,

Figure 12 is a block diagram of an extended personal area data network according to one embodiment of the invention.

DESCRIPTION

A remote monitoring system includes a wearable configuration of sensors and data analysis devices and further includes data models for interpretation of the data collected by the sensors. The sensors monitor human physiology, activity and environmental conditions. In one embodiment, the data analysis devices use the data models to determine whether hazardous conditions exist. In other embodiments, features are derived by bandpass filtering, signal processing operations, or other analytics. Some embodiments provide useful displays to the user, where the displays are based on algorithms operating on and displaying raw data alone and combined with derivative data. In another embodiment, a communications system included in the remote monitoring system sends an alarm when the remote monitoring system detects a hazardous condition. Further alternative embodiments include an extended wearable personal area data network incorporating multiple master devices in communication with on-body sensor devices.

All of these monitoring, interpretation, and proactive communications applications have at their foundation a combination of sensing, real-time statistical analysis, and wireless communications technology. Furthermore, this technology is packaged in a manner that is as comfortable and non-invasive as possible, and puts little additional physical or cognitive burden on the user. It is robust and reliable, unobtrusive, accurate, and trustworthy. It is as simple as possible to operate, and difficult to break. A feature of the system described here is the proactive, robust notification capability provided by the combination of sensing, real-time statistical analysis, and proactive communications. This capability makes it possible to automatically and reliably notify relevant third parties (care-givers, rescuers, team-members, etc.) in the event of emergency or danger.

The body-worn, implanted, and mobile components of the system (hereafter "the wearable") are highly reliable with long battery (or other mobile power-source, e.g. fuel cell) life, so that both the individual being monitored and those who may be required to intervene can rely on its continued operation over a sufficiently long period of time without the constant concern of power failure. To achieve this, an appropriate power source is selected and the electronics are engineered for low power consumption, particularly for processing and communications. Effective low-power engineering involves careful selection of electronic components and fine-grained power management so that particular subsystems (such as a communications radio, microprocessor, etc.) may be put into a standby mode in which the power consumption is reduced to an absolute minimum, and then awakened when needed.

Human Factors

The human factors of the wearable – both cognitive and physical – are important to the overall usefulness of the system. From the cognitive standpoint the wearable is very simple to use, with as many functions as possible automated, so that the wearer can attend to other tasks with minimal cognitive burden imposed by the device. To the extent that the wearable interacts with the user, the interactions are carefully designed to minimize the frequency, duration, and complexity of the interactions. The physical human factors of the wearable are also important; the wearable's physical package is as small and light as possible, and is carefully positioned and integrated with other body-worn (or implanted) elements so that it will not encumber the user, interfere with other tasks, or cause physical discomfort. Sensors, in particular physiological sensors, are carefully selected and placed for measurement suitability, compatibility with physical activity, and to minimize the physical discomfort of the wearer. Weight and size are important design criteria, requiring both miniaturization of electronics and careful low-power design, since power consumption translates directly into battery (or other mobile power source) weight.

Sensing

Not all locations on the human body are equal with regard to the location of physiological sensors, and in many cases it may be desirable to embed sensors or other components of the system in clothing, shoes, protective gear, watches, prosthetics, etc. Wired connections among distributed on-body wearable components are, at times, infeasible due to human factors or usage constraints, and in such cases a suitable wireless personal-area network is integrated that meets the bandwidth, latency, reliability, and power-consumption requirements of the application. Likewise, a suitable local- or wide-area wireless networking technology has been chosen so that the wearable components of the system may communicate with care givers, rescue workers, team members, or other interested parties.

In many cases, a plurality of sensors are appropriate to measure a signal of interest. In some cases no appropriate single sensor exists. For example, there is no single sensor that can measure mood. In others, constraints of the body-worn application make such sensing impractical due to ergonomic considerations or motion artifacts arising from the ambulatory setting. For example, measuring ECG traditionally requires adhesive electrodes, which are uncomfortable when worn over an extended period. Core body temperature is most reliably sensed by inserting probes into body cavities, which is generally not comfortable under any circumstances. Those skilled in the art will recognize that many additional examples could be identified. In some cases these problems can be mitigated through improved sensor technology (e.g. replacing adhesive electrodes with clothing-integrated fabric electrodes for ECG, or the use of a consumable "temperature pill" for core-body temperature measurement). In other cases, however, a constellation of sensors is applicable. The constellation of sensors parameterize a signal space in which the signal of interests is embedded, and then use appropriate signal processing and modeling techniques to extract the signal of interest.

In some embodiments, the constellation of sensors measure a collection of signals that span a higher-dimensional measurement space in which the lower-dimensional signal of interest is embedded. In these alternative embodiments, the lower-dimensional signal of interest is extracted from the higher-dimensional measurement space by a function whose domain is the higher-dimensional measurement space and whose range is the lower-dimensional measurement space of interest. This function involves, for example, a sequence of operations which transform the representation of the original measurement space. The operations further include projecting the higher-dimensional space to a lower-dimensional manifold, partitioning the original or projected space into regions of interest, and performing statistical comparisons between observed data and previously constructed models.

Automated Real-Time Interpretation of Sensor Signals

Throughout this discussion the general term "model" or "model/classifier" is used herein to describe any type of signal processing or analysis, statistical modeling, regression, classification technique, or other form of automated real-time signal interpretation.

Even in situations where the signal of interest is measurable in a straightforward manner that does not burden or discomfort the user, the proper interpretation of this signal may require knowledge of other signals and a the wearer's personal history. For example, it is relatively straightforward to measure heart rate in an ambulatory setting, and increases in heart rate are often clinically meaningful. Simply knowing that the wearer's heart rate is increasing is generally not sufficient to understand the significance of this information. With the addition of information about the wearer's activity state (which can be extracted from the analysis of accelerometer signals) it is possible to distinguish an increase in heart-rate resulting from increased physical activity from one that is largely the result of emotional state, such as the onset of an anxiety attack. Likewise, the cardiovascular response of a fit individual will differ substantially from that of an unfit person. Thus, even for interpreting a relatively straightforward physiological signal such as heart rate, proper interpretation may require additional sensor information as well as additional information about the wearer.

Noise and Uncertainty

Just as measured signals typically contain noise, interpretation typically involves uncertainty. There is a great deal of difference between saying “it is going to rain” and “there is a 35% chance of rain.” Likewise, there is a large difference between an automated interpretation with high confidence and one with low confidence. One source of uncertainty in the interpretation of sensor signals is noise in measurement. Measurement typically involves some degree of noise, and the amount of noise present varies depending on circumstances. For example, many physiological sensors are prone to motion artifacts, and in such cases the amount of noise in the signal is strongly correlated with the amount of motion. Another source of uncertainty lies in the limitations of what can be sensed and modeled – not all relevant parameters can be measured or even known for some important conditions. For example, after decades of research and modeling, the US Army recently discovered when trainees died of hypothermia in a Florida swamp that there was greater variation among various individuals' thermoregulatory capacities than had been previously believed.

In general, models capable of working with and expressing uncertainty are preferable to those which are not. Further, regardless of whether the sensing task is simple or complex, all sensor measurements are a combination of signal and noise, and appropriate analysis techniques takes this into account. Although linear regression, thresholding or other simple modeling and classification techniques may be appropriate for some applications, better results can almost always be obtained through the application of more principled statistical modeling techniques that explicitly take uncertainty into account. This is particularly important for the automated classification of conditions, events, or situations for which there is a high cost for both false-positive and false-negative classification. For example, the failure of a system designed to detect life-threatening injury, cardiac fibrillation, etc. may be life-threatening in the case of a false negative, but expensive and ultimately self-defeating if false positives are common. The Personal Alert Safety System (PASS) alarms presently used by firefighters are a good example of one such dysfunctional alert system because they create a considerable nuisance with their false positive responses, and firefighters are therefore inclined to disengage them or ignore them. The problems associated with false positives may in some cases be mitigated by bringing the wearers into the interaction loop by means such as giving them the opportunity to cancel an automatically triggered call for help. This, however, only transfers the burden from one set of individuals (the rescuers) to another (the wearers). While this may reduce the economic cost of false positives it may also place an unacceptable cognitive burden on the wearer.

Statistical Classification Process

Figure 8 is a flow chart of a statistical classification process according to principles of the invention. Statistical classification is the process by which measured sensor data is transformed into probabilities for a set of discrete classes of interest through the application of statistical classification techniques. The application of the process summarized here to the problem of wearable telemonitoring systems is one of the key innovations embodied in the inventive system. At step 300, an appropriate set of statistical classification models is created (hereafter to be called "model creation"). At step 305, the statistical classification models resulting from the model creation step are implemented on the wearable such that they can be evaluated in real-time using on-body computational resources ("model implementation"). At step 310, the wearable telemonitor system evaluates these models in real-time using live sensor data, the results of which may trigger communications with remote third parties, cause delivery of status information to the wearer, or otherwise play an important role in the behavior of the wearable telemonitor system. This is the "model evaluation" step.

Model Creation

In general, model creation (step 300) is done once for each class of problem or individual user. In alternative embodiments of the invention, the model is continually refined as the models are used (referred to as "on-line learning"). Unless on-line learning is needed, the model creation process can be done off-line, using powerful desktop or server computers. The goal of the model creation process described here is to create statistical classification models that can be evaluated in real-time using only on-body resources.

Model creation starts with data gathering. In one embodiment of the invention, data is gathered through body-worn sensor data. In general, this data is "labeled" so that what the data represents is known. In some embodiments of the invention, there are two data classes, such as "normal heart activity" and "abnormal heart activity." Actual example data from both classes is gathered, although there are situations where simulated data may be used if the acquisition of real data is too difficult, costly, or poses some ethical or logistical challenges.

From analysis of this representative data, appropriate modeling features are chosen to be used by the model Features are derived measurements computed from the "raw" sensor data. For example, derived measurements in one embodiment are created by computing the differential forward Fourier transform (DFFT) or power spectrum from a short-time windowed sequence of data. Features may also be derived by bandpass filtering, signal integration or differentiation, computing the response of filterbanks or matched filters or other signal processing operations. A "trial feature" is a trial operation which is used to test possible model correlations. The analysis process typically includes the computation of several trial features in order to arrive at a final model feature. After features are chosen, an appropriate model type and structure is chosen. Finally, the parameters for the specific model type, structure, and representative data are estimated from the representative data.

In a first example of an application of the present invention, the sensors are used to measure core body temperature and the data model is the likelihood of morbidity due to heat injury. In this example, the collected data can be analyzed directly according to the morbidity model in order to make conclusions about the severity of the injury.

A second example application of the present invention is a cardiac fitness meter using the cardiac interbeat interval (IBI) at rest to determine cardiac fitness of a subject. A system measuring the duration between heart beats is used to determine the IBI. In order to validate this fitness meter, it is examined against an established, widely recognized fitness assessment system such as a cardiac stress test on a treadmill. An appropriately representative study population is selected which can be done using known techniques in experimentation and statistics. Several minutes of IBI data for each subject at rest is then recorded which results in, for example, two hundred numbers. Then, the subjects are evaluated using the treadmill stress test to establish which subjects are "fit" and which are "unfit," thus creating model labels. In this example, the "labels" are a continuum, but data cut-offs can be established for analysis purposes. One example of a data cutoff in this instance is the Army minimum fitness standard. Thus, for each subject, the trial feature is computed from the measured interval data. The trial feature (i.e., the IBI variance) is then plotted against the labels, "fit" and "unfit." An effective fitness meter results in a clear correlation between a higher IBI variance and the "fit" label.

The above examples are simplified, however, the examples demonstrate the point that trial features can be used to construct models to be used with high confidence when using complex, high-dimensional data showing large variations over time or including noise or uncertainty.

Model Implementation

The results of the model creation step (step 300)_ are: (1) the process for calculating model features, (2) the structure and type of the model, and (3) the model parameters themselves. These three elements specify the statistical classifier. Implementing a model evaluation system (step 305) that is capable of evaluating the statistical classifier in real-time using on-body resources is technically challenging. Feature calculation and model class posterior calculation (i.e., calculating the likelihood that an observed feature, or set of features, is modelable by a particular model class) can be computationally intensive. Although it is often possible to do these calculations using very basic computing resources such as inexpensive microcontrollers, doing so requires the careful selection of appropriate computational resources as well as highly optimized software implementations. A component of this is choosing appropriate algorithms and then implementing them using optimized fixed-point arithmetic. For example, the preferred embodiment includes a very fast algorithm for calculating the Fast Fourier Transform of the sensor data using fixed-point arithmetic rather than floating point arithmetic, because a floating point algorithm would be too slow on a microcontroller.

Model Evaluation

The results of model creation and implementation are a system capable of classifying “live” sensor data in real-time using on-body resources. The step of classification (step 310) entails real time comparison of the features calculated from a data stream to the parameters of the model. This matching using Bayesian statistics identifies the "activity" with which the data stream best matches and yields a statistical estimate of the confidence with which the match can be made. The results of this classification process drive the proactive communications features of the wearable and may otherwise complement information acquired from the wearer, from the wearer's profile or history, and from the network in driving application behavior. An example of model evaluation is described below with regard to Figure 7A and Figure 7B.

Distributed vs. Monolithic Wearable Signal Interpretation Architecture – Bandwidth and Power Consumption

The wearable provides sufficient processing power to implement whatever modeling or classification system is necessary for the application. This processing power is provided by local, on-body computing resources, without depending on external computation servers. Modern microcontrollers and low-power embedded processors, combined with low-power programmable digital signal processors (DSPs) or DSP-like field programmable gate arrays

(FPGAs), provide more than enough processing power in small, low-power packages suitable for most on-body applications. Applications which require distributed on-body sensing may also require on-body distributed computation. Accordingly, in those embodiments with distributed on-body sensing, power at the one or more computational centers on the body and personal area network bandwidth consumption are reduced by performing as much signal processing and modeling as possible in the same package as the sensor. This is particularly important in higher-bandwidth distributed sensing applications (such as distributed wearable systems that employ computer vision systems or speech recognition) in which the raw signal bandwidth may strain the capabilities of the personal area network. In addition, even low-bandwidth distributed sensing applications may benefit from distributed processing since the power cost of wireless communications is almost always higher than computation in modern hardware.

Having the capability to process information on-body is supplemented by the ability to send either the products of the analysis or the original raw data, optionally mediated by the results of on-body analysis, to other locations for further analysis or interpretation of data at a location remote from the body. Indeed, the capability to relay raw sensor signals (be they physiological data, environmental conditions, audio or video, etc.) to remote team members, care givers, or rescuers may be important to the planning and execution of an appropriate intervention. As such, the distributed processing model need not be confined to on-body resources, as the wearable supports a local- or wide-area wireless networking capability in order to be able to communicate with other team members, care givers, rescuers, etc. Such communications are expensive in terms of power consumption, and are generally not preferable for routine operation. If, however, the local- or wide-area communications system is being used for other purposes (such as to call for help, or to provide a "back haul" voice communications channel, etc.) this channel can be important to push data out to "heavy weight" processing resources such as remote computer servers. These servers can be used to provide more sophisticated analysis to the remote team or caregivers. They can also be used to provide additional analysis or interaction capabilities to the wearer (such as a speech-based interface), or to allow for real-time adaptation or modification of the on-body modeling or classification system, including firmware updates and the fine-tuning of model parameters. Those skilled in the art will recognize that the precise computational functionality that is performed, and which of it is performed on the body versus remotely will evolve over the years as microcontrollers become smaller, more powerful and less expensive, and as the applications evolve in purpose and implementation.

Reconfigurable Wearable Signal Interpretation Hardware

Since a single set of sensors can potentially be used for many applications, and because models may be improved over time or tailored to the needs of specific individuals (or even be continuously improved through on-line learning techniques) it is important that the signal processing and interpretation hardware be adaptable. In the preferred embodiment, it is to alter model/classifier parameters, change the model structure or type, or add additional models to be evaluated by updating the wearable's software or firmware, without the need to modify or replace hardware. This is accomplished through the use of self-reprogrammable microcontrollers or conventional embedded/mobile processors (the Intel XScale is an example of one such processor). Alternative embodiments use high-performance reconfigurable signal processing hardware for some or all of the computation, such as programmable DSPs or FPGAs.

Human Machine Interaction

Any explicit interaction demands that the wearable imposes on the wearer will typically translate directly into increased cognitive load and likely decreased task performance. This effect has been documented prior to the development of wearable computers in the form of competing tasks experiments in cognitive psychology. As a result of this phenomenon, it is important to design the human-machine interaction system of the wearable to minimize the frequency, duration, and complexity of these demands. Donald Norman's "Seven Stages of Action" provide a useful framework in which to begin to analyze interaction demands. The seven stages of action are: 1. Forming the goal; 2. Forming the intention; 3. Specifying the action; 4. Executing the action; 5. Perceiving the state of the world; 6. Interpreting the state of the world; and 7. Evaluating the outcome. The Design of Everyday Things, Donald A. Norman, Currency-Doubleday, New York, 1988, pp. 46 - 48. In particular interactions are carefully designed to minimize Norman's gulfs of evaluation and execution. id., pp. 49 - 52.

In many cases needed information gathered through explicit interaction with the user can be replaced with information gathered from the automated interpretation of sensor data, augmented with previously stored information and information available through wireless networks. For example, the wearer need not provide location information to rescuers because the information is already available through technologies built into some of the alternative embodiments of the inventive system: a GPS receiver, a dead reckoning system, an RF signal map, or other automated source, taken individually or in some combination.

Using information acquired from other sources to reduce the need for explicit user interaction is an important part of mitigating the cognitive demands imposed by the wearable on the wearer, but does not address the entire problem. Interactions that deliver information to the wearer may interfere with other tasks, even when no explicit input is required. Making such information easily understood -- reducing Norman's "gulf of evaluation" -- is important for reducing the cognitive demands of such interactions. Presenting the wearer with stimuli that require a decision typically interferes with other decision-making tasks. As a result, in the disclosed art any wearable interactions are designed to minimize the presentation of stimuli that require that the wearer make a decision. For example, it would be unreasonable to ask of an airman to remember to turn on his life signs device when he was also involved with making decisions about escaping from a life-threatening situation. Thus, when the device is donned prior to a mission and used with sensors and algorithms to determine whether an airman is alive or dead, it has sufficient battery storage so that it is automatically on and stays on until the airman returns to friendly territory. There is no decision required by the airman to turn it on.

Compatibility with Existing Procedures, Networks, and Equipment

The wearable application is designed for the greatest possible compatibility with existing procedures, activities, and gear used by the wearer. This is important both for reducing the additional training required for effective use of the wearable and to decrease the complications, inconvenience, and expense of adopting the wearable technology.

For military and industrial applications this means that the wearable has been designed to function with standard radio gear and networks, standard or existing communications protocols, normal emergency procedures, etc. By leveraging standard body-worn elements such as hand-held radios for long-range communications or personal digital assistants (PDAs) for user interaction, the overall weight, bulk, and complexity of the wearable system is reduced as well.

For civilian biomedical applications, this means that the wearable is designed as much as possible to be unobtrusive, to be compatible with the widest range of street clothing and routine user activities, and to work with (or replace) conventional body-worn devices such as cell phones, PDAs, etc.

Example Embodiments

Below are described example embodiments of the inventive art constituting the hub, including a variety of alternative embodiments constituting the hub with sensors, peripherals and communications. One embodiment contains its own radio with a range of about 50-100 yards. Another embodiment ties to an electronic device that provides communications to third parties. In another alternative embodiment, a life signs monitor for military personnel uses one of these hubs with sensors to measure heart rate, breathing pattern, GPS (global positioning system), and a three-dimensional accelerometer to measure motion, with selective data sent on demand to an authorize receiver. In another alternative embodiment, a Parkinson's monitor to measure dyskinesia and gait as a means to estimate the need for medication, uses one of the two same hubs, plus accelerometers placed on selected extremities for a period varying from 1 hour to 24 or more hours, with data stored in flash memory or streamed to a separate computer. Still further alternative embodiments employ other combinations of sensors. Those skilled in the art will recognize that the inventive art will support many variations of these same hub, sensor, communications, and linkage configuration for varying purposes. For example, a monitor employing a plurality of sensors can determine a degree of progression of Parkinson's disease or other neurological condition such as stroke or brain lesion that effects for example gait or motion of a patient. Another example monitor according to principles of the invention determines an adverse reaction to, or overdose of, a psychotropic medication. In a further example, a monitor determines the presence and degree of inebriation or intoxication. Still further alternative embodiments includes a monitor that detects a sudden fall by the wearer or an impact likely to cause bodily trauma such as a ballistic impact, being struck by a vehicle or other object, or an explosion in the proximity of the wearer. Still further alternative embodiments include a monitor to determine an acute medical crisis such has a heart attack, stroke or seizure. In one alternative arrangement, the monitor is able to detect a panic attack or other acute anxiety episode. In a further alternative arrangement, the monitor is able to determine from for example unsteady gait or reduced activity that there is frailty, illness or risk of medical crisis. In another alternative embodiment of the invention, the monitor is capable of detecting hazards to which the wearer has been exposed such as biological pathogens, neurotoxins, radiation, harmful chemicals or toxic environmental hazards.

Figure 1 is a picture of a chest strap holding sensors according to the present invention. The chest strap 120 holds sensors securely in proximity to the torso of a person (not shown). Sturdy cloth 100 forms the backbone of the chest strap 120, with soft high-friction cloth 105 placed on the inside to contact the skin of the torso so that the chest strap is optimally held in position. Should this not be sufficient, shoulder straps (not shown) can be attached to provide over-the-shoulder support. The chest strap 120 is cinched to appropriate tightness using a buckle 102 through which the opposite end 101 of the chest strap is fed.

The hooks 103 and eyes 104 of Velcro complete the secure, non-moveable linkage. Wires 107 are used to link one or more sensors in the chest strap 120 to a hub 125, as shown in Figure 2. The wires 107 emerge from conduits in the chest strap 120 leading from pockets or other topological features that hold or otherwise constrain the position of the sensors. Elastic cloth 109 with a spring constant much less than that of a piezo-electric strap 108 provides surrounding surface and structural strength as well as consistent look and feel for that part of the strap. The piezo-electric strap 108 increases and decreases voltage as it is stretched by the user's breathing out and in, thus provides a signal that can be used to determine whether the user is breathing, and if so, certain of the characteristics of that breathing. A pocket 110 holds a Polar Heart Monitor or other R-wave detector or other non-obtrusive heart beat detector, which communicates detailed information about heart beats wirelessly or by wire to the hub 125 (shown in Figure 2), which is attached by Velcro or by other means to the outside of the chest strap, or to another on-body location. Alternative embodiments of the invention use radio communications to connect the sensors in the chest strap 120 to the hub 125 and so do not require the wires 107.

Figure 3 is a block diagram of a first configuration of the hub and sensor placement on a human figure representation 150 according to principles of the invention. The human figure representation 150 is shown wearing a chest strap 120 having sensors (not shown) and a hub 125. The sensors include, for example, a piezoelectric breathing sensor and a polar heart monitor. The hub 125 includes, for example, an accelerometer and analytics. This example configuration of sensors can be used to monitor a patient with Parkinson's disease where pulmonary data, cardiovascular data and motion data are of interest.

Figure 4 is a block diagram of a second configuration of the hub and sensor placement on a human figure representation 150 according to principles of the invention. The human figure representation 150 is shown wearing a hub 125 at the torso and sensors 155 at the wrists and ankles. The hub 125 includes, for example, an accelerometer and a wireless personal area network. The sensors are, for example, accelerometers and may include analytics. The sensors communicate wirelessly with the hub 125 through the wireless personal area network. In an alternative embodiment, the hub 125 and sensors 155 are included in a single on-body device.

Figure 10 shows a jacket including a chest strap for holding sensors similar to the chest strap described above. The cloth of the flight jacket of an airman, the jacket of a policeman, the robe of the elderly person, or other apparel can be made sufficiently sturdy so that, if the clothing is tautly placed around the chest, the clothing is capable of, for example, holding a sensor in a proper position over the heart area of the chest and is also capable of yielding with a suitable elasticity so that a piezo-electric sensor on the strap is able to stretch during inhalation and contract during exhalation while minimizing user discomfort and restriction of motion.

Figure 10 shows a typical jacket 500 with a button closure. The present invention is not limited to the type of garment. Accordingly, alternative embodiments include vests, robes, shirts or other apparel that opens at the front and is re-attached at the front by such means as buttons, zippers or Velcro. A garment like a T-shirt is generally considered to be an inappropriate garment because such a garment requires that it be brought over the head and fitted tightly on the torso so that, for example, it is not readily adjustable, is uncomfortably tight and restricts motion.

The strap 505 for holding sensors in place against the body is attached inside the garment, that is, the jacket 500. The jacket 500 provides initial placement of the strap 505 and any sensors held by the strap. The strap 505 and also any devices held by the strap are substantially hidden by the jacket. The strap 505 includes additional locating mechanisms that are described below with regard to Figure 11.

Figure 11 shows the jacket 500 opened so that the inside of the jacket is visible. The strap 505 is attached to the inside 510 of the jacket 500. Alternatively, the sensors are attached directly to the inside of the jacket, which may be semi-elastic and reinforced for strength. The strap 505 has an extended end 515 that includes a Velcro portion (or some other type of suitable fastening material) on the outer surface configured and located to couple with a complementary Velcro portion 525 on the second end 530 of the strap 505. Accordingly, the Velcro portion on the outside 520 surface of the extended end 515 connects to the complementary Velcro portion 525 inside the jacket 500. The wearer, therefore, is able to place the strap on himself or herself. In some embodiments, the jacket 500 is fitted so that there is approximately one-quarter of the body circumference, that is, from approximately the center of the left side of the chest area to approximately the center of the ventral side of the chest area for Velcro contact between the two ends of the strap 505. Other fit arrangements, including the mirror image, are possible within the scope of the invention. It is generally important to fit the jacket 500 (or other garment) so that the wearer is able to readily and rapidly "wrap" the jacket 500 into proper position. Once the initial connection of the strap 505 is made with itself, the left side of the jacket 500 is brought to the center front where it is buttoned, zipped, or otherwise connected in the conventional means (or innovative means are also allowed, such as a Velcro attachment) that makes the jacket 500 appear to be a normal jacket 500.

In an alternative embodiment, the clothing is donned and doffed normally, with cordlocks 535 used to set the tightness of the chest strap area. Fed around the strap area through the clothing at the level of the sensor package at the chest, and then through the cordlocks 535 are semi-elastic cords 540. The semi-elastic cords may be made of any one of a number of materials such as rubber, metal cable, and fiber cording. The present invention is not limited to those materials listed here. The term semi-elastic refers to the property of allowing expansion and contraction of the chest cavity while at the same time providing enough resistance so that the transducer remains sensitive to breathing motions. When more of a cord 540 is pulled through a cordlock 535, the strapping around the chest is held tighter. Such cordlocks 535 are available in a range of sizes, types, and strength of grip on the cord. Some hold the cord in place by pinching the cord with a constant friction, while others hold the cord in place by chocking the cord so that the more the cord pulls to reduce the tension on the chest strap, the more tightly the cord is held in place by the cordlock.

In yet another embodiment, particularly useful for first responders and military personnel who are at risk, there is an inflatable "balloon" 545 positioned around the chest area in the vicinity of the sensors. There are many possible balloon configurations within the scope of the present invention including a long balloon over the entire circumference of the chest strap area. When an event occurs that indicates that the person is at risk (e.g. if the analysis device determines that there has been a ballistic impact, or if an airman ejects from his cockpit), then the electronics automatically inflates this balloon 545, pressing the sensors with the suitable pressure against the chest area so that the sensors will provide valid outputs. The electronics meters the success of this inflation, and later maintains the inflation, in part by metering pressure and in part by determining the quality of sensor output. Inflation means include, for example, a small battery-driven air pump as well as a battery-powered, computer controlled valve for a very small liquefied $CO2$ canister. Other inflation devices are also possible within the scope of the present invention.

Integrating the strap 505 into a garment such as the jacket 500 provides a number of advantages. First, the strap 505 may be integrated into the normal outerwear of the user. Second, the strap 505 integrated into a jacket provides a ready means for the wearer to don and doff the chest strap. Third, it provides the wearer with means to set it to a tension that allows ready breathing while at the same time providing sufficient tension around the chest area so that the sensors are able to detect such bio-events as heartbeat and breathing. This includes means to set the clothing in approximately and rapidly in the position needed for the sensor system to work properly, which means will often be sufficient. It also includes a variety of means to provide fine adjustment of a tightness of the clothing around the chest. Finally, it includes means for the on-body electronic hub to provide feedback to the wearer indicating whether the clothing is set properly so that the sensors are detecting the required body functions.

Figure 5 is a block diagram of the hub and sensor network 200 according to the present invention. The hub and sensor network 200 includes a hub 125 connected through a first wired or a wireless personal area network (PAN) 205 a variety of sensors 210, 215, 220, 225. Sensors A 210 are without proactive communications abilities and instead are polled for data by the hub 125. Sensors B 215 are without proactive communications abilities however do include analytics. Sensors C 220 include both proactive communications and analytics. Sensors D 225 include proactive communications but are without analytics. The hub 125 is also connected to a PDA 230, or some other portable wireless communications device such as a cell phone, through a second wireless network 235. The hub 125 is further connected to an external local area network (LAN) or external computer system 240 through a wired or wireless connection 245. The hub 125 is still further connected to user interface peripherals 250 through a wired or wireless connection 255. The PDA 230 and external computer system 240 are connected through a wired or wireless connection 260.

In operation, the hub 125 communicates with and controls the sensors 210, 215, 220, 225, directing the sensors 210, 215, 220, 225 to collect data and to transmit the collected data to the hub 125. Those sensors 220, 225 with proactive communications send collected data to the hub 125 under preselected conditions. The hub 125 also communicates with and controls the user interface peripherals 250. The hub 125 further communicates with portable devices such as the PDA 230 and with external network or computer systems 240. The hub 125 communicates data and data analysis to the peripherals 250, portable devices 230 and external systems 240.

The hub and sensor network 200 shown here is merely an example network. Alternative embodiments of the invention include a network 200 with fewer types of sensors, for example, including a network 200 with only one type of sensor. Further alternative embodiments include a network 200 with a hub 125 connected to only a PDA 230. In still further alternative embodiments, the various devices in the network 200 are able to communicate with each other without using the hub as an intermediary device. In short, many types of hub, sensor, communications devices, computer devices and peripheral devices are possible within the scope of the present invention. The present invention is not limited to those combinations of devices listed here.

Sensor Hub Module with Internal Radio

Figure 6A, Figure 6B, Figure 6C and Figure 6D together are a schematic diagram of a first sensor hub according to principles of the invention. Figure 6A shows a first part of the first sensor hub, Figure 6B shows a second part of the first sensor hub, Figure 6C shows a third part of the first sensor hub and Figure 6D shows a fourth part of the first sensor hub. The core of the sensor hub module in the preferred embodiment is an Atmel ATMega-8L micro-controller of Atmel Corporation of San Jose, California. The micro-controller is connected to two unbuffered analog inputs, two buffered analog inputs, two digital input/outputs, RS232, I2C, and two Analog Devices ADXL202E 2-axis accelerometers. One accelerometer is mounted flat on the sensor hub board, and the other is mounted perpendicular on a daughter board. This configuration allows for the detection of 3-axis acceleration.

The buffered analog inputs are composed of one AN1101SSM op-amp for each input. One of these op-amps is configured as a ground referenced DC amplifier, and the other is configured as a 1.65 Volt referenced AC amplifier. A third AN1101SSM provides a stable output for the 1.65 Volt reference.

The RS232 is routed to either the Cerfboard connector or to the Maxim MAX233AEWP RS232 line level shifter. This allows the sensor hub to be connected to the Cerfboard through the logic level serial or to other devices through RS232 level serial. The I2C bus is also routed through the Cerfboard connector to allow for alternative protocols to be used between the sensor hub and the Cerfboard.

All the devices except the RS232 line level shifter use the 3.3 Volt power rail. The line level shifter uses the 5 Volt power rail, and the 5 Volt power rail is also routed to the Cerfboard through its connector.

Power Module

The power module is composed of a Linear Technology LTC1143 dual voltage regulator, a Linear Technology LT1510-5 battery charger, and related passive components for both devices. The LTC1143 provides a switching regulated 3.3 Volt output and a 5.0 Volt output for input voltages that vary from 6 Volts to 8.4 Volts when running from the battery or 12 Volts to 15 Volts when running off an external power supply. The LT1510-5 charges a 2-cell Li-Poly battery using a constant I-V curve at 1 Amp when a 12 Volt to 15 Volt external power supply is used.

Life Signs Telemonitor Low-Power 2.4GHz

Figure 7A, Figure 7B, Figure 7C and Figure 7D together are a schematic diagram of a second sensor hub according to principles of the invention. Figure 7A is a first portion of the hub, Figure 7B is a second portion of the hub, Figure 7C is a third portion of the hub and Figure 7D is a fourth portion of the hub. This hub is designed to provide sensor information over a short range radio link.

In the present application, the term "short range" is applied to wireless communications signals which, for reasons of the underlying physics and/or the specific details of the engineering application, attenuate more rapidly than RF propagating in free space, which is to say more rapidly than a factor of $1/r^2$, where r is the distance from the transmitter. Examples of such "short range" communications modalities include: near-field inductive communications, near-field capacitive communications, body-coupled acoustic communications, UV free-space optics or other free-space optical communications using light frequencies rapidly scattered and attenuated by the atmosphere. A human body-coupled acoustic system relies on the impedance mismatch between the body and surrounding air to prevent signal (in this case, sound) leakage. In effect, the body itself acts as a wave-guide to confine the signal. Such modalities are distinguished from "non-short-range communications", the category that includes all other wireless communications modalities, even so-called "short range RF" communications, which are attenuated proportionally to the square of the distance from the transmitter (or less rapidly, as in the case of planar RF waves).

By using a simple short range radio, the protocol can be handled on a lower power microcontroller. This reduces the space and power requirements from the 802.11 embodiment by not requiring a single board computer. The low power telemonitor is a single unit of hardware constructed from three modules.

The first module provides the power regulation system which outputs a 3.3 Volt power rail. The module can also optionally support a 5.0 Volt power rail and battery charger. The modules can run off of a Li-Poly 2-cell battery or a 12 volt regulated power source. These power rails are capable of handling loads of up to 450 mA. A power rail also charges the battery when an external power source is supplied. Due to the lower power requirements of this system, this module takes up less area and has shorter components than those used on the 802.11 system.

The second module contains the sensor hub and is nearly identical to the 802.11 version in terms of functionality. The difference is that the low power version provides its data via I2C to the third module instead of via RS232 to the Cerfboard.

The third module contains the low power, short-range radio system. This module takes the sensor data from the sensor hub module over I2C and transmits it over a short range 2.4 GHz radio link. The module may also be configured as a receiver for the sensor data transmissions, transferring the data to the destination data collection system over RS232 or I2C.

Sensor Hub Module

The core of the sensor hub module is an Atmel ATMega-8L micro-controller. The micro-controller is connected to two unbuffered analog inputs, two buffered analog inputs, two digital input/outputs, RS232, I2C, and two Analog Devices ADXL202E 2-axis accelerometers. One accelerometer is mounted flat on the sensor hub board, and the other is mounted perpendicular on a daughter board. This configuration allows for the detection of 3-axis acceleration.

The buffered analog inputs are composed of one AN1101SSM op-amp for each input. One of these op-amps is configured as a ground referenced DC amplifier, and the other is configured as a 1.65 Volt referenced AC amplifier. A third AN1101SSM provides a stable output for the 1.65 Volt reference.

The RS232 is routed to both a logic level connector or to the TI MAX3221CUE RS232 line level shifter. This allows the sensor hub to be connected to other devices through the logic level serial or RS232 level serial. The I2C bus is connected to the adjacent modules to handle the routing of sensor data between modules.

Radio Module

The radio module is composed of an Atmel ATMega-8L micro-controller and a Nordic VLSI nRF2401 2.4GHz transceiver. The nRF2401 provides a 2.4Ghz 1Mbit short range wireless RF link. The micro-controller configures and handles all communications between the nRF2401 and the rest of the system.

The micro-controller has an I2C connection to the adjacent modules to allow it to transport sensor data to and from other modules on the system. It also connects to a TI MAX3221CUE RS232 line level shifter to allow the radio module to operate as a radio transceiver for an external device such as a laptop or PDA.

These modules contains all the needed passive components for the nRF2401 to operate in 1Mbit mode including a PCB etched quarter wave antenna.

Power Module

The power modules contains 2 Maxim MAX750A switching power regulators, a Linear Technology LT1510-5 switching battery charger, and related passive components for each device. One MAX750A is configured to output a 3.3 Volt power rail, and the other is configured to output a 5.0 Volt power rail. Each of these rails is limited to 450 mA of current load. The input voltages to these regulators vary from 6 Volts to 8.4 Volts when running from the battery or is 12 Volts when running from an external regulated power supply. The LT1510-5 charges a 2-cell Li-Poly battery using a constant I-V curve at 1 Amp when a 12 Volt regulated external power supply is used.

FFT and Classifier Module

The Fast Fourier Transform ("FFT") software is programmed in machine language on the Atmel processor. Because the Atmel computational capabilities are limited, the volume of data to be transformed substantially in real time is considerable, the FFT algorithm needs to run very fast. An algorithm using floating point is not generally compatible with present Atmel technology because floating point algorithms run too slow. Transforming the algorithm into fixed point made it possible for the algorithm to run with sufficient speed and with acceptable use of microcontroller resources.

Sensor information is input to the FFT algorithm, which computes the Fourier Transform as output. Such transformation of the original data into the frequency domain aids data analysis particularly in cases in which the phenomena are fundamentally oscillatory. Examples of such oscillatory data are ambulatory motion, heart beat, breathing, and motion on a vehicle that is traveling. This output is then input to a Classifier module, which analyzes and recognizes the pattern or patterns inherent in the data and compares them to patterns it has been trained to recognize using a statistical algorithm. The Classifier module output consists of one or more matched patterns along with the confidence level for the match.

Figure 9 is a flow chart of the process of the Classifier module.

At step 400, the Classifier module executes the following:

For each accelerometer sample, do:

three axis accelerometer sample → {fixed-point magnitude operator}

→ one magnitude value

At step 405, the Classifier module executes the following:

For each "window" of, for example, 64 accelerometer magnitude values (50% overlap), do:

64 magnitude values → { fixed point DFFT operator }

$\rightarrow$ { power spectrum (mag square) operator }

$\rightarrow$ thirty one spectral features.

Sample numbers are typically any power of two. If a larger number of values is used, more memory is generally required.

At step 410, the Classifier module executes the following:

For each vector of 31 spectral features, do:

for each class (Gaussian mixture model) i of n, do:

31 spectral features $\rightarrow$ { Gaussian mixture model i}

$\rightarrow$ s_i (class score for model i)

Result is n unnormalized class scores.

At step 415, the Classifier module executes the following:

For each unnormalized s_i, do:

$s_i \rightarrow$ { normalization operator}

$\rightarrow$ p_i (class posterior probability for class i)

Result is class posterior probabilities for each class, given the window of 31 spectral features.

The display of the output information in the presently preferred embodiment is a listing of patterns matched along with confidence levels. Those skilled in the art will recognize that many alternative displays can be useful. Examples of such displays include a red-yellow-green light for each of one or more matches, and a color coded thermometer with the color representing an action to be taken and the height of the indicator a measure of the confidence with which the Classifier determined this to derive from a correct data-model match.

The manner in which the information is visualized is supportive of the core feature of "alarming" based on the output of the classifier. The core feature of the "proactive telemonitor" is that it is proactive. In some embodiments of the invention, nothing is displayed until the health state classifier (or environmental conditions classifier, the injury classifier, etc.) detects that there is a problem, and calls for help. This implementation is feasible because it utilizes principled classification to drive proactive communications and user interaction rather than merely displaying information or sending an alarm upon the overly simplistic criterion of some data parameter being exceeded.

In alternative embodiments of the present invention, other types of microcontrollers other than the Atmel microprocessor may be used. Many low complexity, basic microprocessors are suitable for use in the present invention. The present invention is not limited to the microprocessors listed here.

Figure 12 shows an alternative embodiment of the wearable personal area data network (WPADN or "extended network") described above. The network 600 shown in Figure 12 is an extended personal area data network (XWPADN) which is a network that generally uses more than one communication modality and generally uses more than one "master" node.

Therefore, according to one embodiment of the invention, the network 600 includes three master nodes 605, 625, 640. A plurality of sensors 610, 615, 620 are connected to a first master 605 over communications links 612, 616, and 622 respectively. In this embodiment, the master 605 and sensors 610, 615, 620 are an on-body network 635 where the master 605 is similar to the hub 125 of Figures 3 and 4. Master 625 is in communication with master 605 over communications link 637 and with sensor 616 over communications link 641. Master 625 is in communication with master 630 over communications link 645.

In the present embodiment, the communications links 612, 616, 622 may be either wired or wireless links. Communications links 637, 641 in the present embodiment are wireless links while communications link 645 may be either wired or wireless. In alternative embodiments of the invention, the communications links may be some other combination of wired and wireless. As will be described below, a variety of protocols may be used over the communications links 612, 616, 622, 637, 641, 645.

The XWPADN protocol is generally implemented on top of the low-level link protocols provided by the underlying communications modalities. Typically, the XWPADN protocol is packet-based, employs multiple channels, and uses time domain multiple access (TDMA) channel sharing to allow multiple devices to share a small number of communications channels. The XWPADN protocol employs a star topology. In addition, embodiments of the extended network include a plurality of master devices as shown in Figure 12. In these multi-master networks, a single slave device, such as a sensor, may report to more than one master, or two master devices may directly exchange information in a peer-to-peer network configuration. The extended network has further topological flexibility in that the star-topology network is extended with master-to-master communications links in addition to multimaster communications.

The extended network such as the network 600 of Figure 12 uses mixed-mode short range (non-RF) wireless communications. The extended network includes the capability of using zero or more additional short-range wireless communications modalities, such as the combination of near-field inductive communications and UV communications, or more than one type of inductive near-field communications modes (e.g., a low-power, low-bandwidth modulation scheme with a higher-power, high-bandwidth).

Further, the extended network such as the network 600 uses mixed-mode short-range and non-short-range wireless communications. In some embodiments, short range, non-RF communications links are combined with RF systems, either to provide a longer-range communications capability in combination with the personal area network, to support legacy RF equipment or to provide increased bandwidth through the use of low-signature high-bandwidth RF communications techniques, such as pulse-shaped baseband modulation, otherwise known as Ultra-Wide Band (UWB). Use of other high bandwidth, low-signature RF communications techniques are considered to be within the scope of the present invention.

The extended network such as the network 600 combines short-range communications and passive or active wired (or other physical transmission media) extensions, on-body or off. For example, the use of a conventional wired digital communications (or mixed digital and analog) communications system for sensors integrated into a shirt or jacket using a short-range wireless communications link (such as inductive near-field) to communicate with another network in close proximity, such as a gear harness worn over the garment, the network in another garment, or a communications network in a vehicle, chair, etc.

The extended network such as the network 600 supports light-weight abstractions (and in some cases full implementations) of standard digital protocols, such as IP and TCP running over the XWPADN network. For some applications, the XWPADN functions in integration with other wireless or wired data networks. For example, XWPADN masters or XWPADN/IP network bridge nodes could perform network protocol translation and abstraction to make XWPADN master nodes appear as standard IP nodes. Support is not limited to IP and TCP protocols listed here. One skilled in the art will understand that the use of other standard wired and wireless protocols is possible within the scope of the invention. Further one skilled in the art will understand also that the use of higher-level protocols such as HTTP, the Enchantment IPC protocol, etc. is possible within the scope of the invention.

Topological Flexibility

The extended network such as the network 600 employs a star network topology so that a network master such as master 605 may manage the bandwidth allocated to each slave device, such as the sensors 610, 615, 620, discover new slaves, and generally manage the network in a centralized way. While this is a desirable network topology for many foreseeable applications of the WPADN, it is not the only useful network topology for short-range communications. Exceptions may include applications involving a mixture of on-body and off-body communications, or applications involving hybrid networks (combinations of XWPADN, and other types of short, medium, or long-range networks).

The extended network in some embodiments uses a protocol that supports zero or more masters communicating with a single slave, thus allowing "overlapping" short-range networks. This functionality is useful in a variety of situations. For example, one application of on-body short-range digital networks is physiology monitoring for soldiers. During routine operation, an on-body master node would interrogate body-worn slave nodes (such as sensors 610, 615, 620) to obtain physiology and activity information to determine health, metabolic load, etc. If, however, a soldier is injured a multi-master functionality would be important for combat casualty care. A multi-master capability would allow a medic or battlefield medical station to directly interrogate the soldier's physiology sensors (XWPADN slave nodes) regardless of the state of the soldier's own XWPADN master, which might be damaged or otherwise inaccessible. Another application for multi-master communications is a network in which a master node is integrated into a chair or vehicle, which would occasionally interrogate nearby slaves (such as the nodes being worn by the vehicle pilot or chair occupant) to determine whether such nodes required recharging, and to perform inductive charging of any nodes that required it.

Another feature of the XWPADN protocol according to certain embodiments of the present invention is direct bidirectional peer-to-peer communications between master nodes, such as master 625 and master 630 shown in Figure 12, or (in some specialized situations) dedicated point-to-point bridge links. In master peer-to-peer mode, this configuration enables nearby masters to exchange information without the additional power drain involved in multi-master communications. For example, in the combat casualty care scenario described above, the medic could reduce the overall power drain on the soldier's physiology sensors by interrogating the soldier's master node, if that master node is still operational. The reason master-to-master communications burns less power than multi-master communications can be explained as follows: Slaves typically send the same type of information to both masters (in a two master network example). Further, slaves typically send on a similar communications duty cycle. As a result, a slave communicating with two masters tends to burn twice the power in transmission as a slave communicating with only one. If the same information is of interest to both masters, then one master may interrogate the slaves and then pass the information on to the other master. This saves power overall and shifts the increased power burden to a master node, which (since the master is necessarily transmitting more frequently than the slaves) is likely to have more spare power capacity.

A point-to-point bridge link is also foreseen as part of the XWPADN application. Such a link could be created between two masters, between a master and a dedicated XWPADN bridge node, or between two dedicated XWPADN bridge nodes. The use of a dedicated bridge node instead of a master may be desirable for some applications since a dedicated bridge node would implement only those protocol functions required for the network bridge and hence would be simpler and less expensive. The network bridge application is described in more detail below.

<u>Mixed Mode Short Range Communications</u>

The extended network includes a plurality of short-range communications modalities, generally a base modality and one or more other modalities. These additional modalities are, in some embodiments, as similar to the base modality as variations on the base modality near-field inductive modulation scheme that trade off increased bandwidth for power consumption. These modalities are, in some embodiments, as dissimilar as a combination of a body-coupled acoustic base modality, and an ultra violet (UV) free-space optics and capacitive near-field extended modalities. Other short-range communications modalities are considered to be within the scope of the present invention.

Multi-modal short-range communications are a desirable feature because no single short-range communications mode may be optimal for a given application. For example, one near-field inductive technology may have a low power cost for running a receiver, but a high power cost for running the transmitter. Likewise, another technology may provide higher bandwidth but at a significantly higher power cost for activating a receiver. A hybrid network combining the low-power base modality with the high-power extended modality could provide better power efficiency and higher bandwidth than either modality alone.

<u>Mixed Mode short-range and propagating RF communications</u>

For some personal area networking applications, it may be desirable to combine short-range communications modalities (such as inductive near-field) with RF communications, either to provide a necessary longer-range communications capability or to achieve higher bandwidth than can be supported by the short-range communications modalities or to support legacy RF systems. The XWPADN supports the use of RF for extended modalities, including the use of legacy 2.4 GHz and 5.8GHz RF protocols such as Bluetooth and WiFi. The use of mixed mode short-range and RF communications decreases the benefits of using true short-range communications modalities, but there are situations which may call for both.

One such situation is the combination of newer XWPADN gear with legacy RF systems. While a "network bridge" approach (see below) could be used to integrate two separate networks, in many applications it may be simpler and more efficient to support the RF network as an extended XWPADN communications modality. Another plausible scenario is the routine use of a true short-range base modality and the occasional use of a high-bandwidth RF extended modality, such as UWB, when the need for greater bandwidth outweighs the penalties in spectrum clutter and (for military or intelligence applications) the increased risk of standoff detection. Returning to the body-worn soldier physiology example previously discussed, it might be necessary for a medic to transfer a large quantity of medical history and/or recorded physiology data from a soldier's XWPADN network, and providing an option to do this quickly (at the cost of an increased RF signature) might be a valuable feature. In addition, the simultaneous use of a true short-range communications channel and a higher-power non-short range channel has security benefits, as the true short-range channel can be used to exchange authentication tokens and symmetric cryptography keys with little risk of eavesdropping, thus allowing highly secure communications on the non-short-range channel without the complexity and key-management and distribution problems of public key cryptography.

Combination of short-range wireless and passive or active wired modalities.

The extended network uses, in some embodiments, wired (or physical medium channeled) communications first-class communications modalities. Both active and passive wired (or physical medium) modalities are used in embodiments of the present invention for short-range communications.

An active XWPADN wired communications modality is simply a conventional wired data bus employing XWPADN protocols. Such a wired bus is, in some embodiments, used to link several digital sensors together within the same body-worn garment. Zero or more active wired channels may be used in combination with wireless modalities in an XWPADN network. In some embodiments, the short-range wireless modalities are used to link between wired XWPADN segments. For example, a primarily wired XWPADN segment integrated into a shirt or jacket might communicate to a primarily wired XWPADN segment through a short-range wireless link located at the point of nearest overlap of the garments. By reducing the operational range of the wireless segment to the smallest possible distance, the power requirements for short-range wireless communication can be drastically reduced.

The passive use of physical media to channel short-range communications is also an important feature of the extended network of the present invention. An example of such is the use of body-coupled acoustic transducers for a body-area acoustic digital network. By using transducers with a significantly stronger coupling to the body than the surrounding air, the acoustic energy is primarily confined to the body itself, with minimal leakage into the surrounding air (the impedance mismatch at the body-air boundary serves to reflect the majority of the energy back into the body at the frequencies contemplated for this application.) In this case, the use of the passive physical medium is important to the operation of the communications modality. Physical media may also be used to extend and direct the reach of primarily wireless short-range signals, such as ferrous metal being used to extend and direct an inductive near-field wireless network. For example, specially designed ferrous elements in a patient-transport gurney might improve the coupling between the body-worn XWPADN sensor nodes of an injured soldier and a nearby medic's XWPADN.

Support for Existing Digital Network Protocols through XWPADN Networks

In many cases XWPADN systems will be required to operate in combination with other types of wired and wireless data networks. In such instances it may be desirable or important for these networks to exchange data. Embodiments of the extended network of the present invention support such interoperability and data exchange through the use of network bridging nodes and protocol translation.

A network bridging node is an XWPADN node with an additional “foreign” network interface. The job of the network bridging node is to bridge appropriate network traffic between the XWPADN network and the foreign network. For example, a network bridging node in the seat of a vehicle might be used to exchange data between the occupant's network and the vehicle's own digital network – perhaps allowing the occupant to use the vehicle's communications systems through the occupant's body-worn interfaces.

In order to exchange data between the XWPADN and the foreign network, typically the network bridging node provides appropriate data translation and abstraction for both networks. For example, if the foreign network is an IP (Internet Protocol) network, it will generally be necessary to for the network bridging node to provide the XWPADN network one or more effective IP addresses, and to abstract the various data sources on the XWPADN as either TCP or UDP sockets. Likewise data received from the IP network will be translated into the form of an XWPADN master-to-master or a slave-to-master communication. In general, this process may be described as a protocol abstraction, where the salient information from one network encapsulated in one protocol is abstracted from its specific protocol representation so that the information may be appropriately recoded in another protocol suitable for another network. To the extent to which there is no simple match in functionality or structure between XWPADN and foreign network protocols, it will be up to the network bridging node to provide whatever additional functionality and resources are required to perform the appropriate abstraction and translation. For example, TCP/IP packets may arrive out-of-order. The bridge node in this example needs to buffer and reassemble the contents of the packets in-order before handing off the contents to the XWPADN.

It is to be understood that the above-identified embodiments are simply illustrative of the principles of the invention. Various and other modifications and changes may be made by those skilled in the art which will embody the principles of the invention and fall within the spirit and scope thereof.

We claim:

CLAIMS

1. A wearable hub for a remote monitor device, the hub positioned on the body of a living being, comprising:

a data receiver to receive transmitted data from at least one sensor positioned on the being, the data receiver to receive transmitted data in a first communications modality;

an analysis device to take the received data as input, the analysis device to determine a condition of the being in response to the data; and

a transmitter to transmit the condition to a second receiving device, the transmitter to transmit the condition in a second communications modality.

2. The wearable hub of claim 1 wherein the second receiving device is an external device.

3. The wearable hub of claim 1 wherein the analysis device further comprises a data classifier, the data classifier employing statistical classification techniques to determine the condition from the received data.

4. The wearable hub of claim 1 wherein the transmitter transmits to a plurality of external devices.

5. The wearable hub of claim 1 wherein the transmitter transmits to the external device using a plurality of communications modalities.

6. The wearable hub of claim 1 wherein the analysis device further comprises a data classifier, the data classifier employing statistical classification techniques to determine the condition from the received data and wherein patterns of data are organized into data classes and the data classifier determines the condition according to which data class the received data belongs.

7. The wearable hub of claim 1 wherein the analysis device further comprises a model analysis system, the model analysis system storing model data and associated rules, the model analysis system to determine the condition by applying the model data and associated rules to the received data.

8. An extended personal area network, comprising:

a plurality of sensors placed on a living body, the sensors to transmit data in a first communications modality;

at least one analytic device to analyze data from at least one of the plurality of sensors, the analytic device to determine a condition of the body; and

a hub to control the plurality of sensors and the at least one analytic device, the hub to communicate the condition to a receiving device, the transmitter to transmit data in a second communications modality.

9. The extended personal area network of claim 8 wherein one of the sensors communicates a condition to a second receiving device.

10. A remote monitoring device, comprising:

a plurality of on-body sensors;

an on-body hub receiving data input from the plurality of on-body sensors, the on-body hub to determine a condition from the received data, the on-body hub to communicate the condition to a second receiving device; and

a chest strap holding the on-body sensors and the on-body hub in place.

11. The remote monitoring device of claim 10 wherein the chest strap is integrated into a garment.

12. The remote monitoring device of claim 11 wherein the garment acts as a locating mechanism for the chest strap.

13. The remote monitoring device of claim 11 wherein the garment includes cording located in the garment with regard to the chest strap such that the cording provides a means to position the chest strap and the on-body sensors.

14. The remote monitoring device of claim 11 wherein the garment includes an inflatable pack that provides a means to position the chest strap and the on-body sensors.

15. The remote monitoring device of claim 14 wherein the inflatable pack is inflated in response to a particular event.

16. A personal area data network, comprising:

a plurality of sensors placed on a living body;

at least one analytic device to analyze data from at least one of the plurality of sensors, the analytic device to determine at least one condition of the body; and

a first hub to control the plurality of sensors and the at least one analytic device;

a second hub in communication with at least one of the first hub and the plurality of sensors; and

a third hub in communication with the second hub.

17. The personal area data network of claim 16 wherein the at least one analytic device further analyzes quality of the data from the at least one of the plurality of sensors.

18. The wearable hub of claim 1 wherein the first communications modality is a wireless communications modality.

19. The wearable hub of claim 18 wherein first communications modality is selected from the group consisting of a radio-frequency communications modality, an inductive near-field communications modality, and an ultraviolet communications modality.

20. The wearable hub of claim 1 wherein the second communications modality is a wireless communications modality.

21. The wearable hub of claim 20 wherein the second communications modality is selected from the group consisting of a radio-frequency communications modality, an inductive near-field communications modality, and an ultraviolet communications modality.

22. The wearable hub of claim 4 wherein the plurality of external devices are on the body.

23. The wearable hub of claim 4 wherein the plurality of external devices located on close physical proximity to the body.

24. The extended personal area network device of claim 8 wherein the first communications modality is a wireless communications modality.

25. The extended personal area network device of claim 24 wherein first communications modality is selected from the group consisting of a radio-frequency communications modality, an inductive near-field communications modality, and an ultraviolet communications modality.

26. The extended personal area network device of claim 8 wherein the second communications modality is a wireless communications modality.

27. The extended personal area network device of claim 26 wherein the second communications modality is selected from the group consisting of a radio-frequency communications modality, an inductive near-field communications modality, and an ultraviolet communications modality.

28. The extended personal area network device of claim 8 wherein at least two of the plurality of sensors communicate using different communications modalities.

29. The extended personal area network of claim 9 wherein the second receiving device is a second hub.

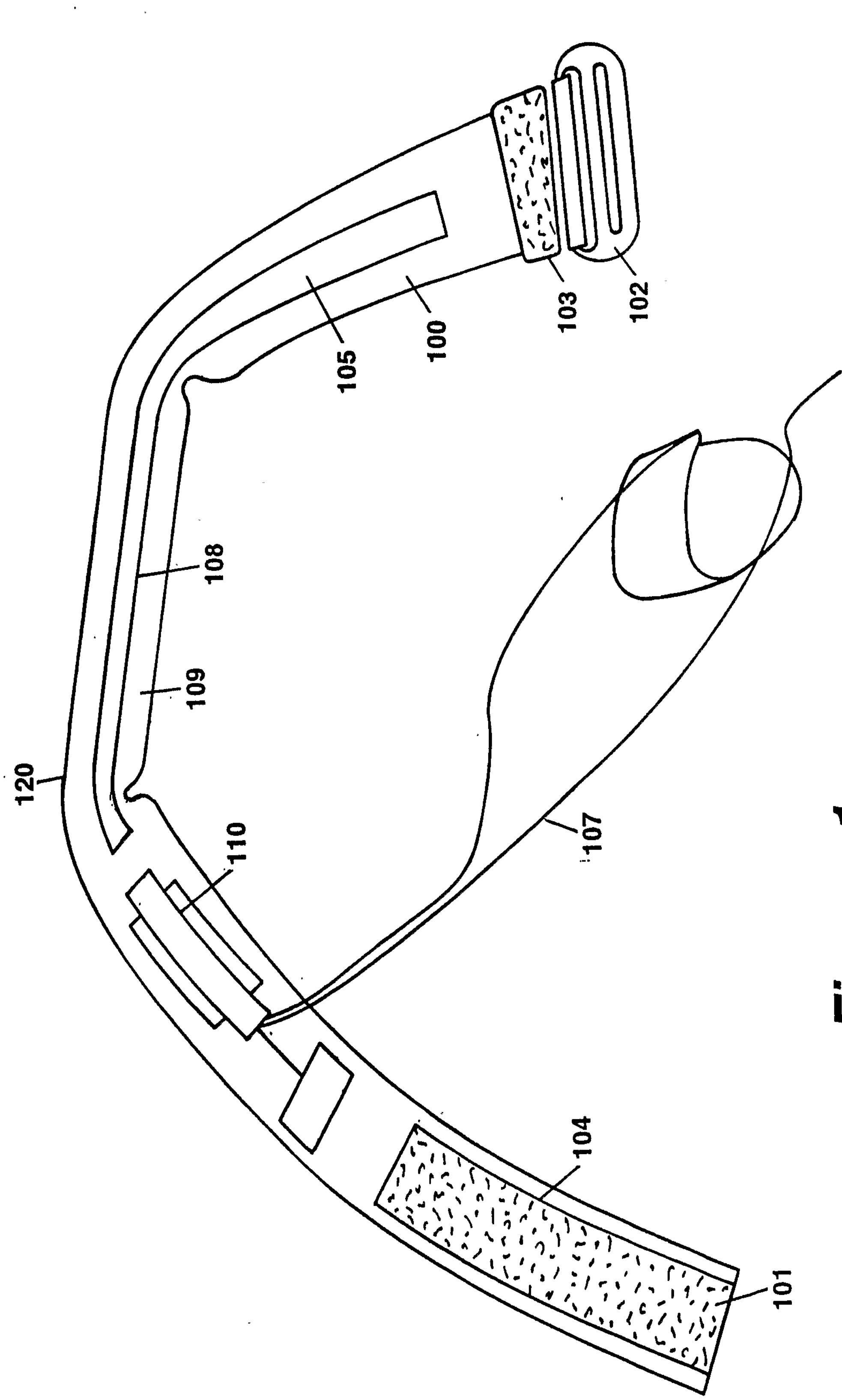


Figure 1

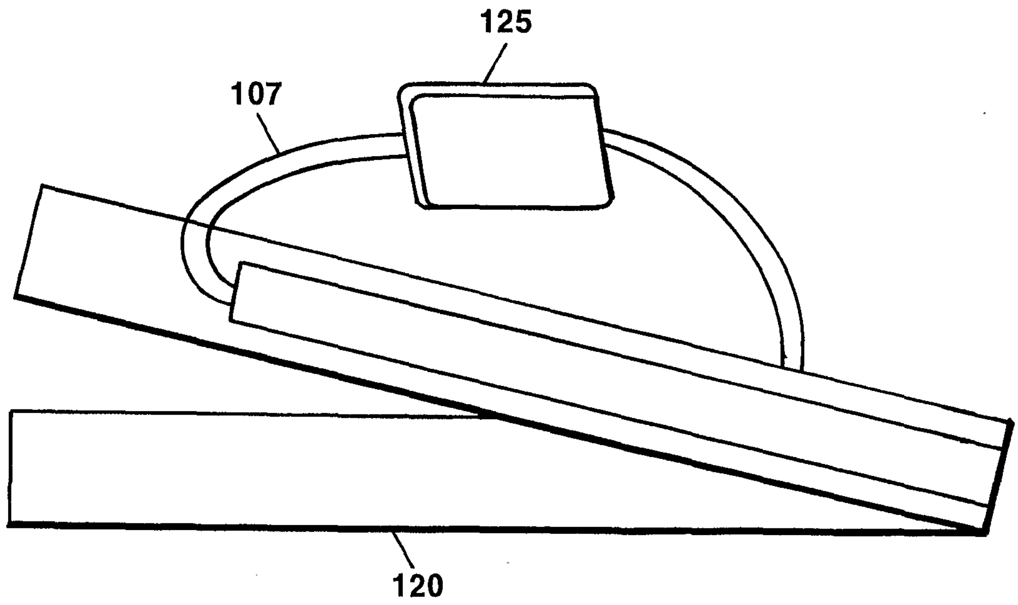


Figure 2

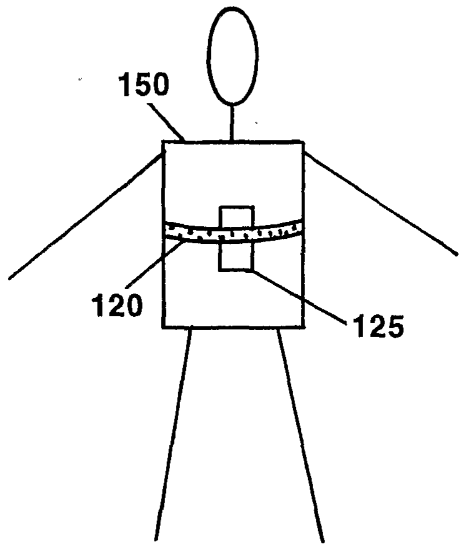


Figure 3

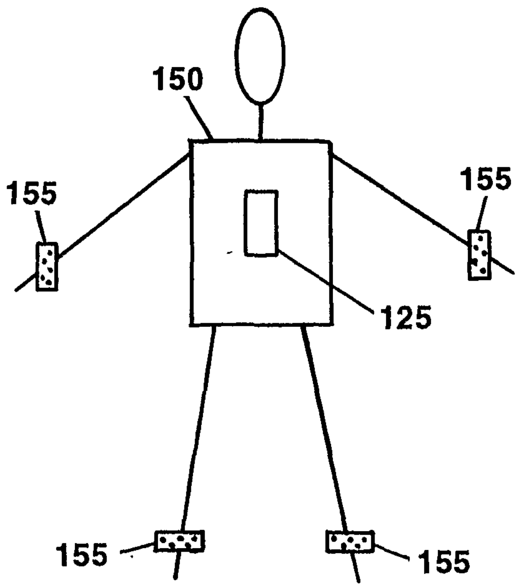
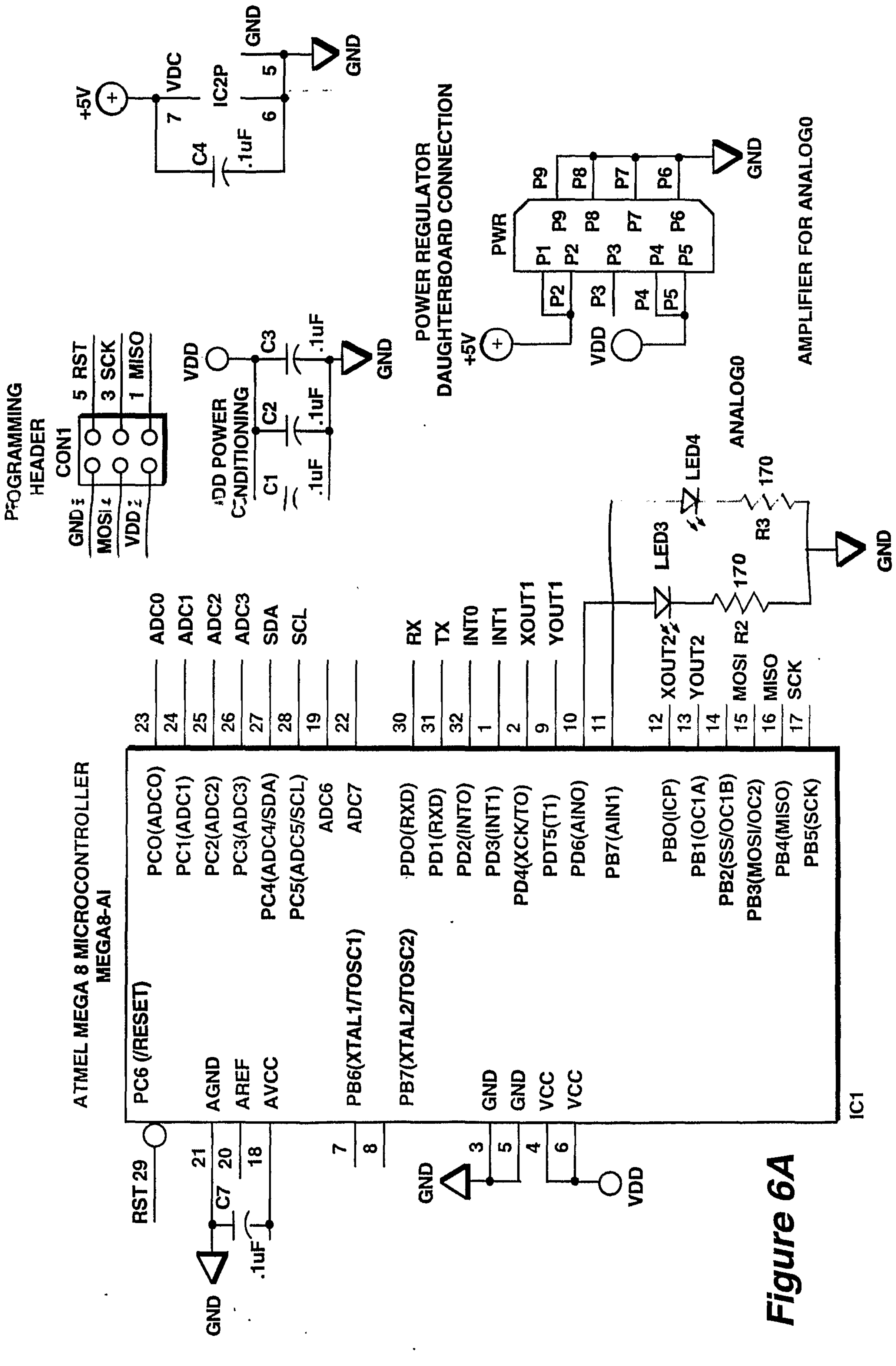


Figure 4



ATMEL MEGA 8 MICROCONTROLLER
MEGA8-AI
IC1
PC6 (/RESET)
AGND
AREF
AVCC
PB6(XTAL1/TOSC1)
PB7(XTAL2/TOSC2)
GND
GND
VCC
VCC
PCO(ADCO)
PC1(ADC1)
PC2(ADC2)
PC3(ADC3)
PC4(ADC4/SDA)
PC5(ADC5/SCL)
ADC6
ADC7
PDO(RXD)
PD1(RXD)
PD2(INTO)
PD3(INT1)
PD4(XCK/TO)
PDT5(T1)
PD6(AINO)
PB7(AIN1)
PBO(ICP)
PB1(OC1A)
PB2(SS/OC1B)
PB3(MOSI/OC2)
PB4(MISO)
PB5(SCK)
ADC0
ADC1
ADC2
ADC3
SDA
SCL
RX
TX
INT0
INT1
XOUT1
YOUT1
XOUT2
YOUT2
MOSI
MISO
SCK
RST 29
C7
.1uF
GND
VDD
PROGRAMMING HEADER
CON1
GND
MOSI
VDD
5 RST
3 SCK
1 MISO
VDD POWER CONDITIONING
C1
C2
C3
.1uF
VDD
+5V
VDC
IC2P
C4
POWER REGULATOR DAUGHTERBOARD CONNECTION
PWR
P1
P2
P3
P4
P5
P6
P7
P8
P9
LED3
LED4
R2
R3
170
ANALOG0
AMPLIFIER FOR ANALOG0

Figure 6A

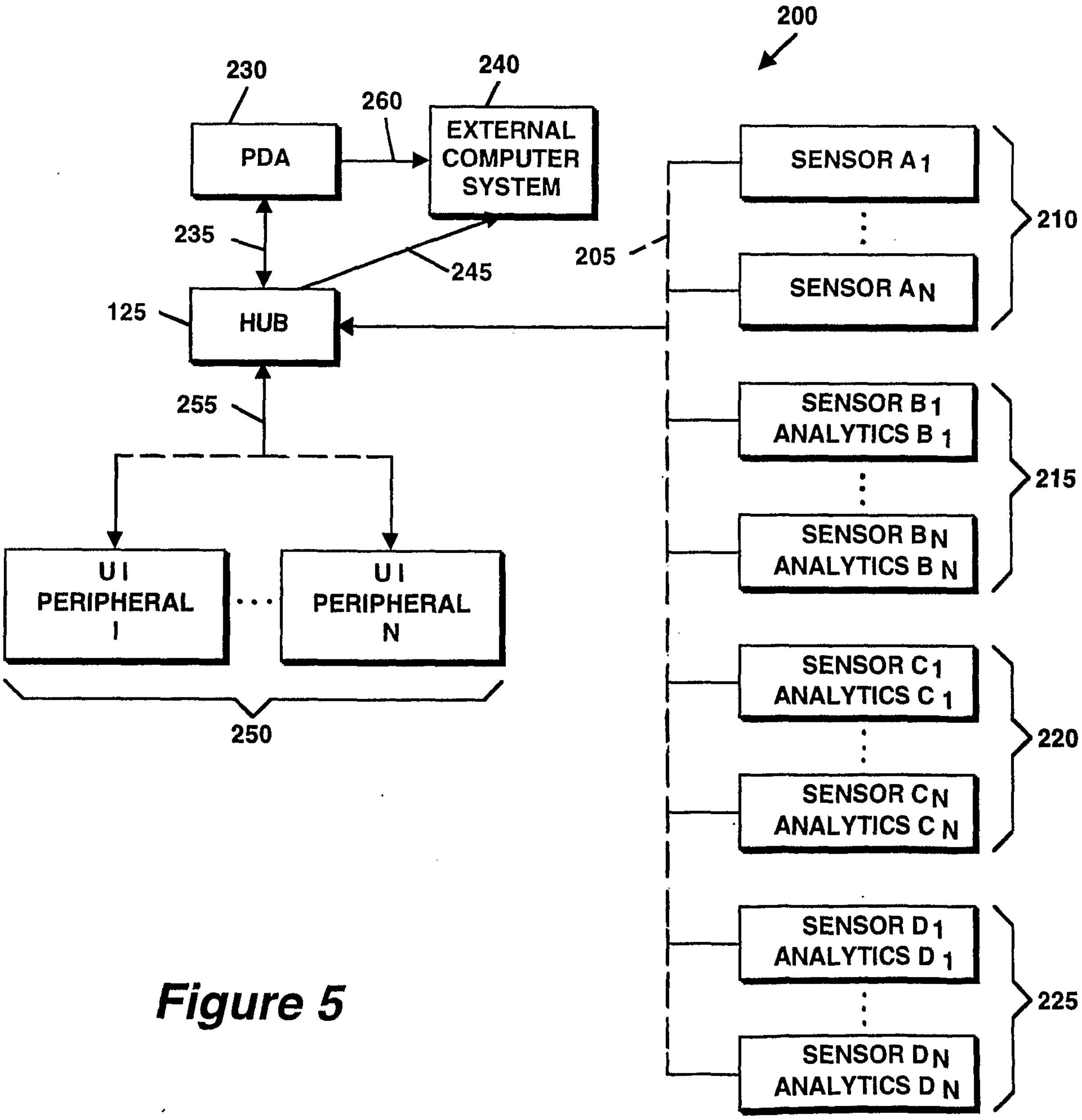

200
230
240
260
PDA
EXTERNAL COMPUTER SYSTEM
235
245
205
125
HUB
255
U I PERIPHERAL I
U I PERIPHERAL N
250
SENSOR A 1
SENSOR A N
210
SENSOR B 1 ANALYTICS B 1
SENSOR B N ANALYTICS B N
215
SENSOR C 1 ANALYTICS C 1
SENSOR C N ANALYTICS C N
220
SENSOR D 1 ANALYTICS D 1
SENSOR D N ANALYTICS D N
225

Figure 5

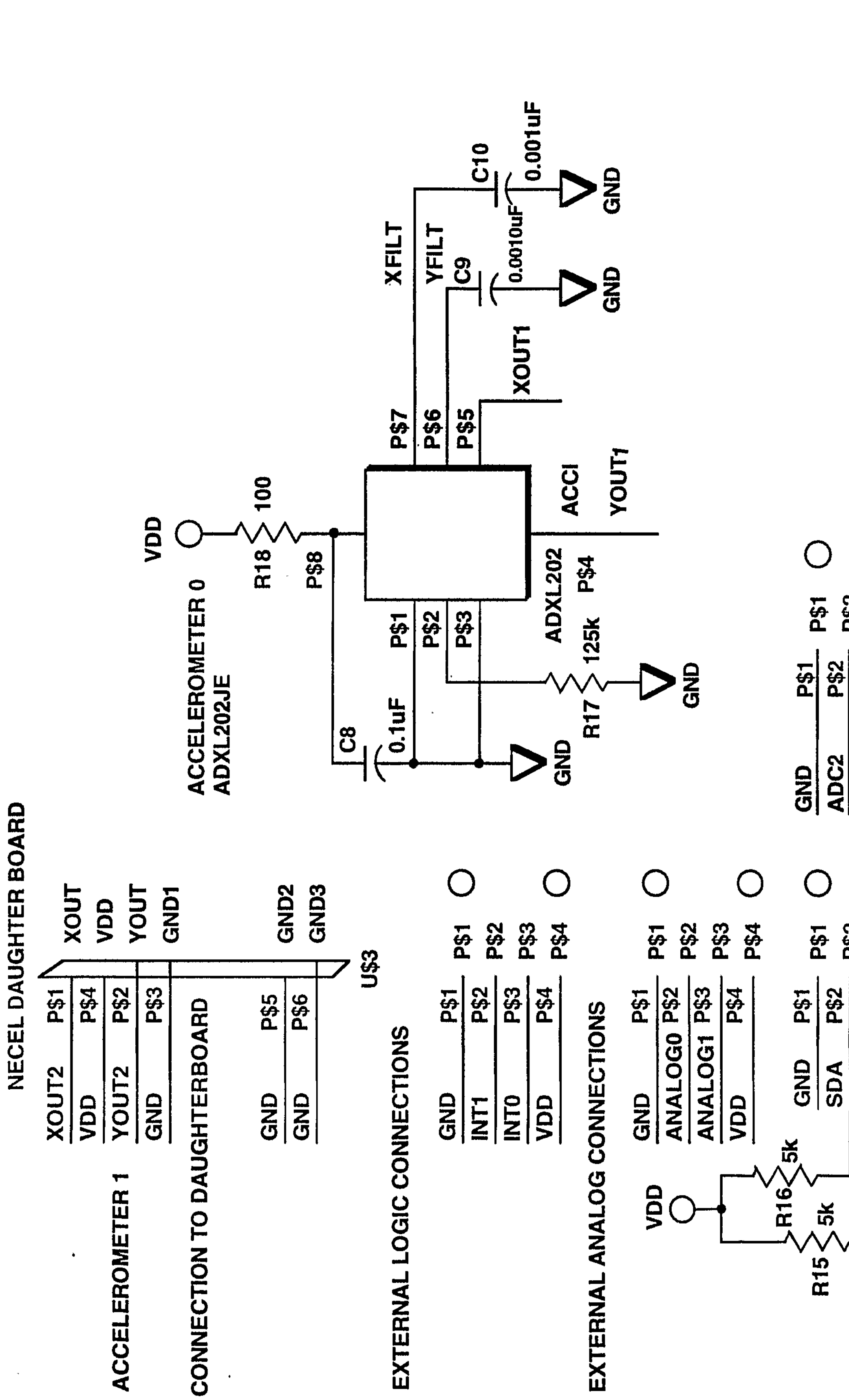

NECEL DAUGHTER BOARD
ACCELEROMETER 1
XOUT2 P$1
VDD P$4
YOUT2 P$2
GND P$3
XOUT
VDD
YOUT
GND1
CONNECTION TO DAUGHTERBOARD
GND P$5
GND P$6
GND2
GND3
U$3
EXTERNAL LOGIC CONNECTIONS
GND P$1
INT1 P$2
INT0 P$3
VDD P$4
EXTERNAL ANALOG CONNECTIONS
GND P$1
ANALOG0 P$2
ANALOG1 P$3
VDD P$4
GND P$1
SDA P$2
SCL P$3
VDD P$4
VDD
R16 5k
R15 5k
ACCELEROMETER 0
ADXL202JE
VDD
R18 100
P$8
C8 0.1uF
GND
P$1
P$2
P$3
R17 125k
GND
ADXL202
P$4
ACCI
YOUT1
P$7
P$6
P$5
XOUT1
XFILT
YFILT
C9 0.0010uF
GND
C10 0.001uF
GND
GND P$1
ADC2 P$2
ADC3 P$3
VDD P$4

Figure 6B

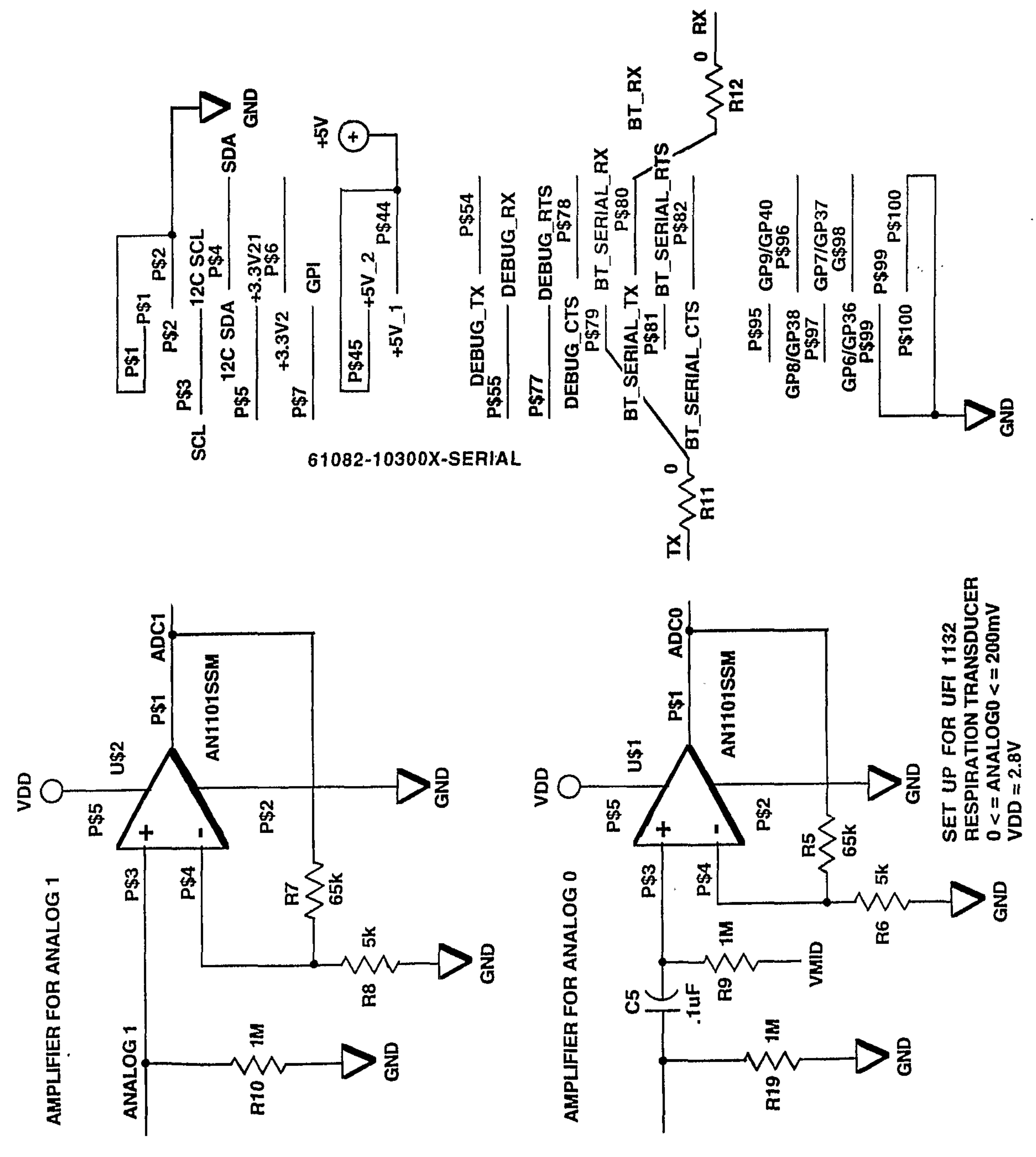

AMPLIFIER FOR ANALOG 1
ANALOG 1
R10
1M
GND
VDD
P$5
U$2
P$3
P$4
P$2
P$1
ADC1
AN1101SSM
R7
65k
R8
5k
AMPLIFIER FOR ANALOG 0
U$1
ADC0
C5
.1uF
R9
1M
VMID
R19
R5
R6
SET UP FOR UFI 1132
RESPIRATION TRANSDUCER
0 < = ANALOG0 < = 200mV
VDD = 2.8V
61082-10300X-SERIAL
SCL
12C SCL
12C SDA
SDA
+3.3V21
+3.3V2
GPI
+5V
+5V_1
+5V_2
P$44
P$45
DEBUG_TX
DEBUG_RX
DEBUG_RTS
DEBUG_CTS
BT_SERIAL_RX
BT_SERIAL_TX
BT_SERIAL_RTS
BT_SERIAL_CTS
BT_RX
BT_TX
TX
RX
R11
R12
GP9/GP40
GP8/GP38
GP7/GP37
GP6/GP36
P$100
P$99

Figure 6D

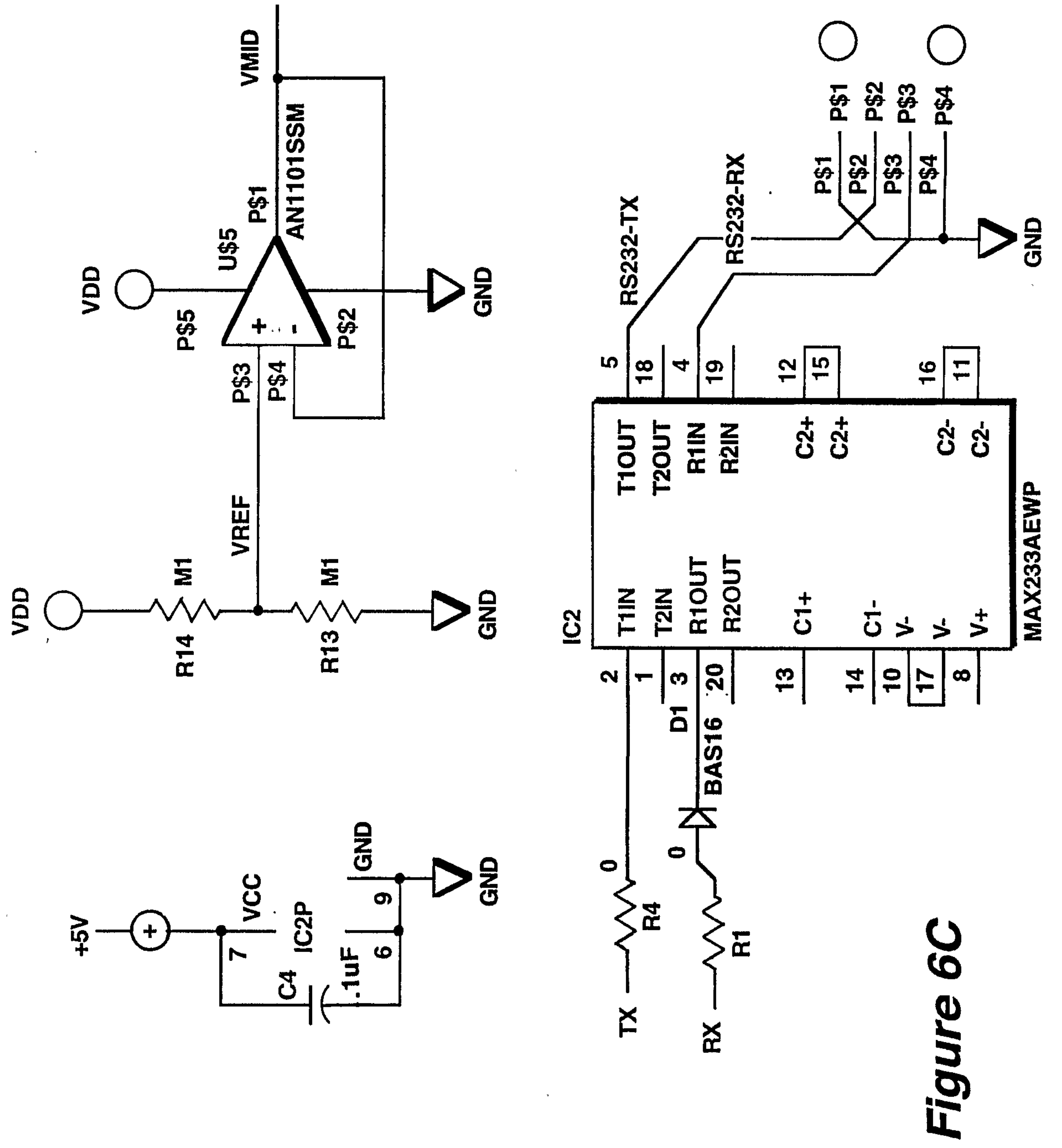

VMID
AN1101SSM
P$1
U$5
VDD
P$5
P$2
P$3
P$4
GND
VREF
M1
R14
R13
+5V
VCC
IC2P
7
6
9
C4
.1uF
IC2
MAX233AEWP
T1IN
T2IN
R1OUT
R2OUT
C1+
C1-
V-
V+
T1OUT
T2OUT
R1IN
R2IN
C2+
C2-
RS232-TX
RS232-RX
TX
RX
R4
R1
D1
BAS16

Figure 6C

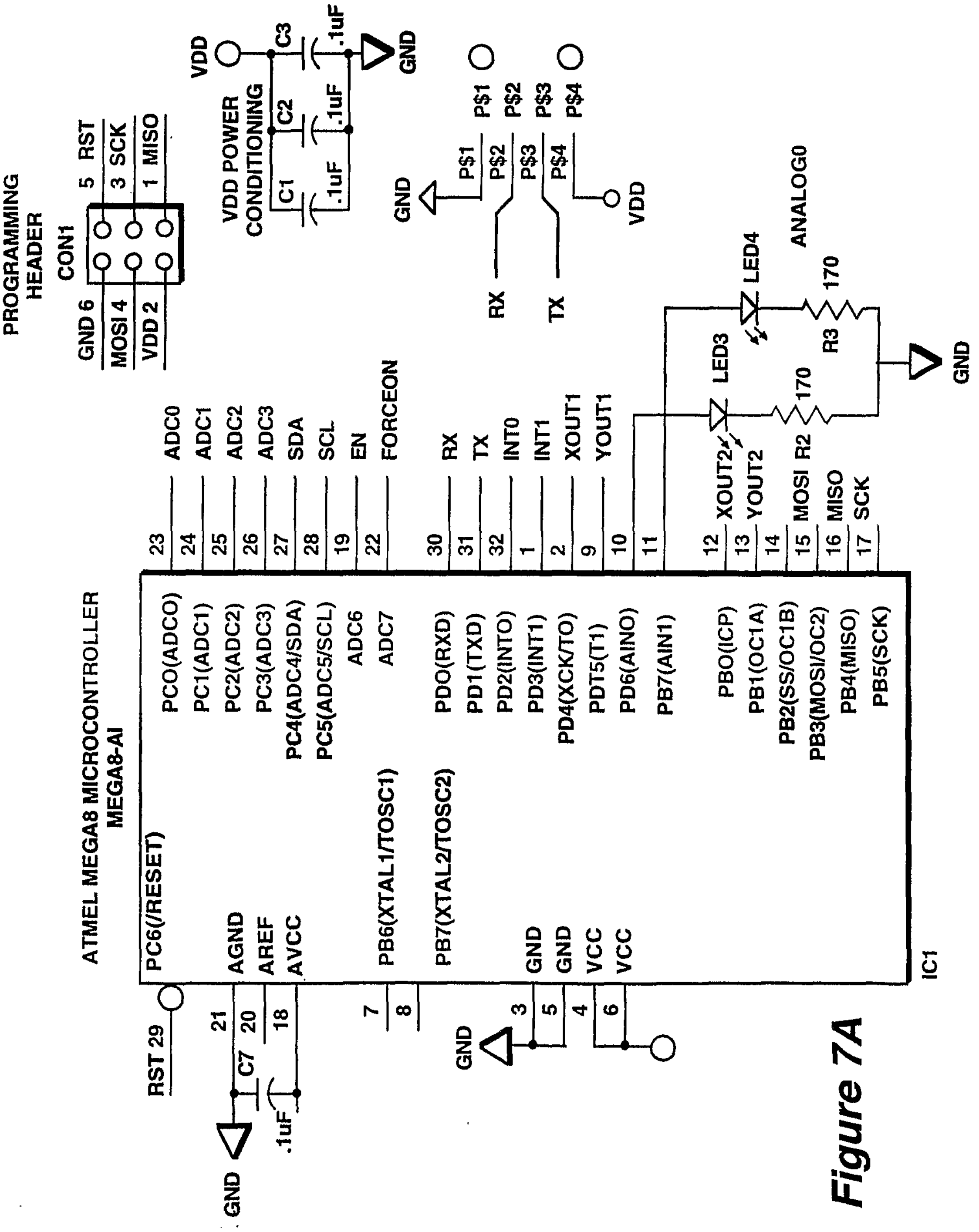

PROGRAMMING HEADER
CON1
GND 6
MOSI 4
VDD 2
5 RST
3 SCK
1 MISO
VDD
VDD POWER CONDITIONING
C1
.1uF
C2
.1uF
C3
.1uF
GND
P$1
P$2
P$3
P$4
RX
TX
ANALOG0
LED4
LED3
R3
170
R2
170
ATMEL MEGA8 MICROCONTROLLER
MEGA8-AI
PC6(/RESET)
AGND
AREF
AVCC
PB6(XTAL1/TOSC1)
PB7(XTAL2/TOSC2)
GND
GND
VCC
VCC
PC0(ADC0)
PC1(ADC1)
PC2(ADC2)
PC3(ADC3)
PC4(ADC4/SDA)
PC5(ADC5/SCL)
ADC6
ADC7
PD0(RXD)
PD1(TXD)
PD2(INT0)
PD3(INT1)
PD4(XCK/T0)
PD5(T1)
PD6(AIN0)
PD7(AIN1)
PB0(ICP)
PB1(OC1A)
PB2(SS/OC1B)
PB3(MOSI/OC2)
PB4(MISO)
PB5(SCK)
ADC0
ADC1
ADC2
ADC3
SDA
SCL
EN
FORCEON
RX
TX
INT0
INT1
XOUT1
YOUT1
XOUT2
YOUT2
MOSI
MISO
SCK
RST 29
C7
.1uF
IC1

Figure 7A

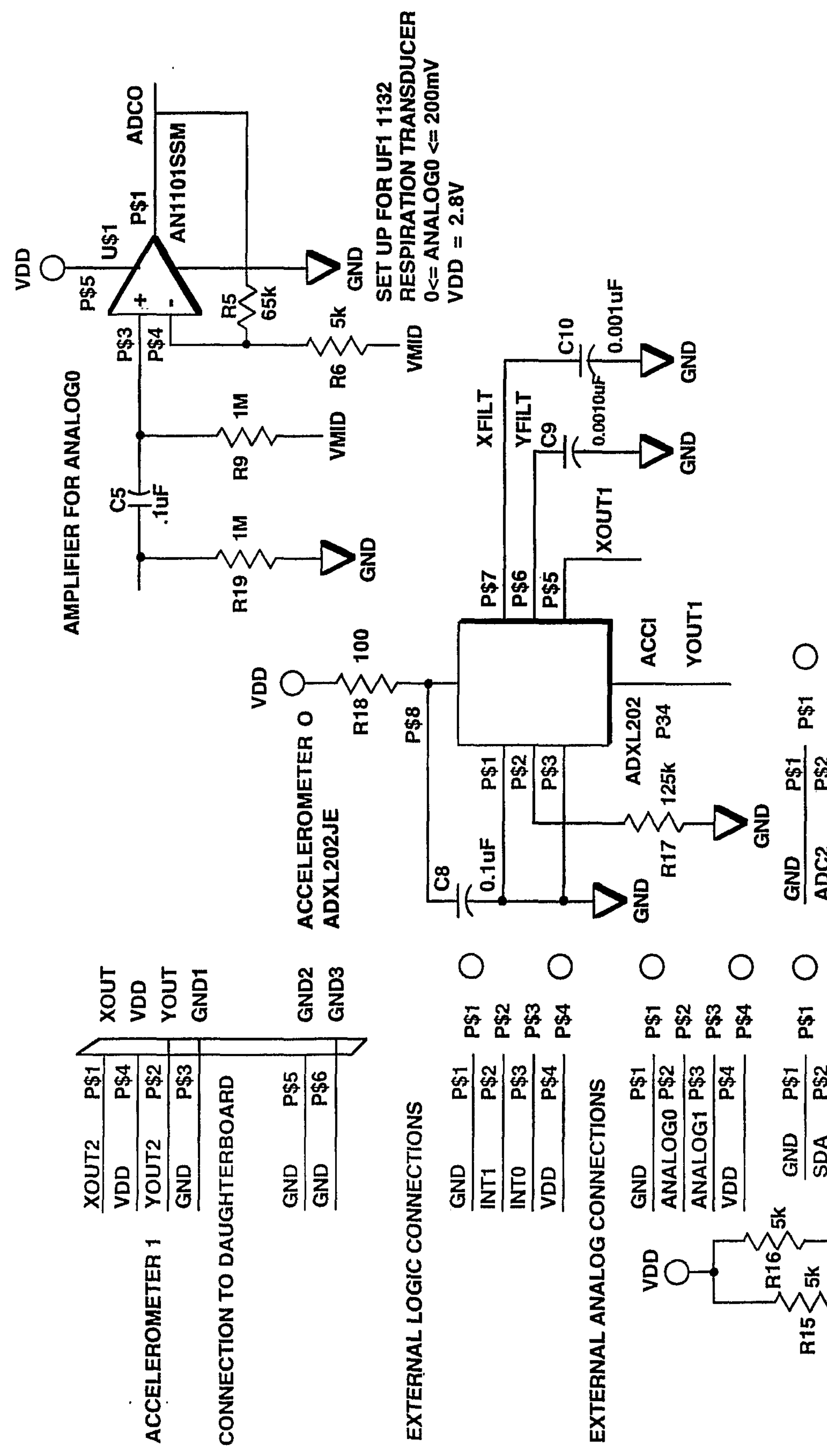

AMPLIFIER FOR ANALOG0
VDD
U$1
P$1
ADCO
AN1101SSM
GND
P$5
P$3
P$4
R5
65k
5k
R6
VMID
SET UP FOR UF1 1132
RESPIRATION TRANSDUCER
0<= ANALOG0 <= 200mV
VDD = 2.8V
C5
.1uF
R9
1M
R19
ACCELEROMETER 0
ADXL202JE
R18
100
P$8
P$7
P$6
P$5
XFILT
YFILT
C9
0.0010uF
C10
0.001uF
XOUT1
ACCI
YOUT1
ADXL202
P34
P$1
P$2
P$3
R17
125k
C8
0.1uF
ACCELEROMETER 1
XOUT2
YOUT2
XOUT
YOUT
GND1
GND2
GND3
P$4
P$6
CONNECTION TO DAUGHTERBOARD
EXTERNAL LOGIC CONNECTIONS
INT1
INT0
EXTERNAL ANALOG CONNECTIONS
ANALOG0
ANALOG1
SDA
SCL
R16
R15
ADC2
ADC3

Figure 7B

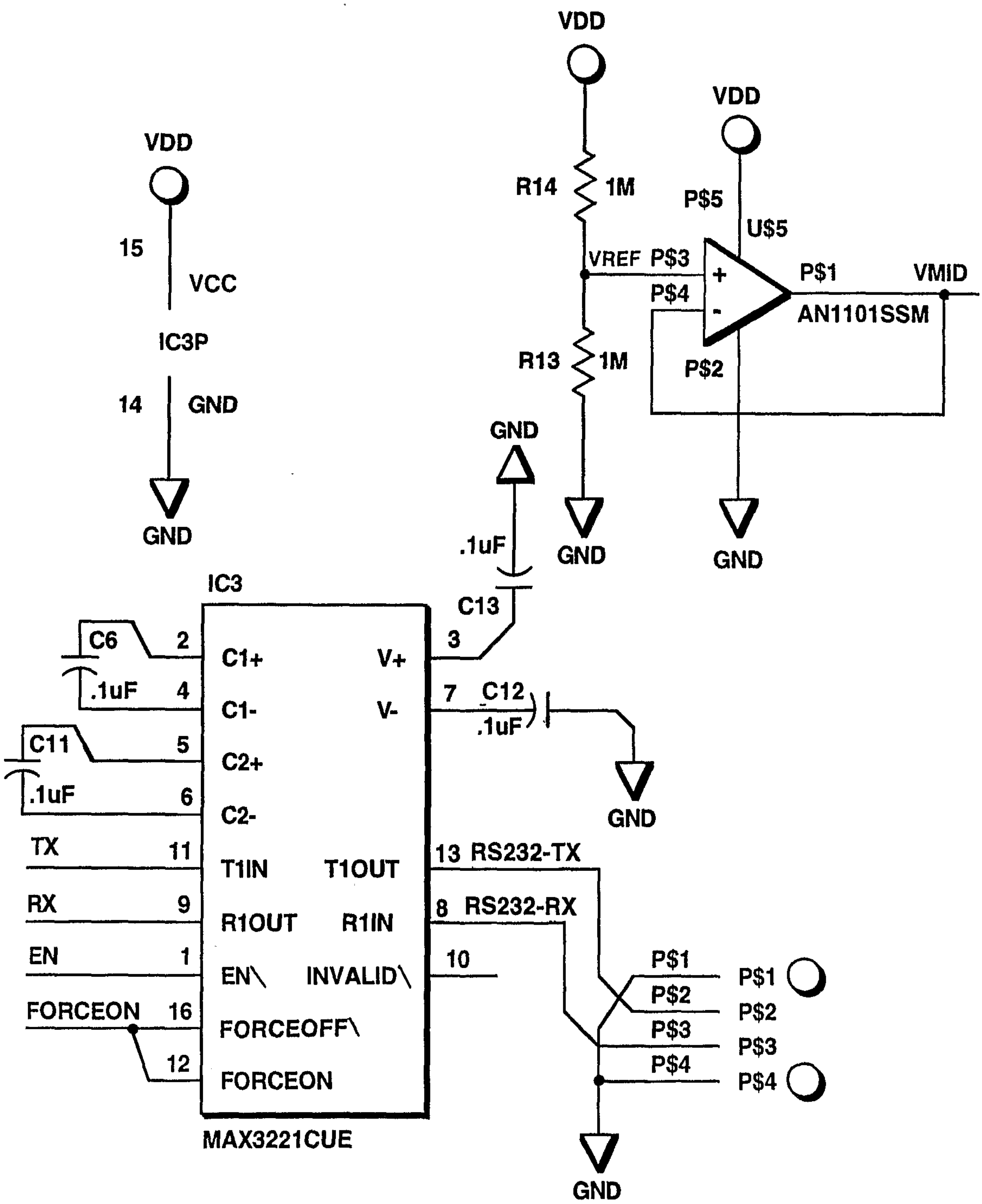

VDD
15
VCC
IC3P
14
GND
GND
VDD
R14
1M
VREF
P$3
P$4
R13
1M
GND
VDD
P$5
U$5
P$1
VMID
AN1101SSM
P$2
GND
GND
.1uF
C13
IC3
C6
.1uF
C11
.1uF
2
4
5
6
C1+
C1-
C2+
C2-
V+
V-
3
7
C12
.1uF
GND
TX
11
RX
9
EN
1
FORCEON
16
12
T1IN
R1OUT
EN\
FORCEOFF\
FORCEON
T1OUT
R1IN
INVALID\
13 RS232-TX
8 RS232-RX
10
P$1
P$2
P$3
P$4
P$1
P$2
P$3
P$4
GND
MAX3221CUE

Figure 7C

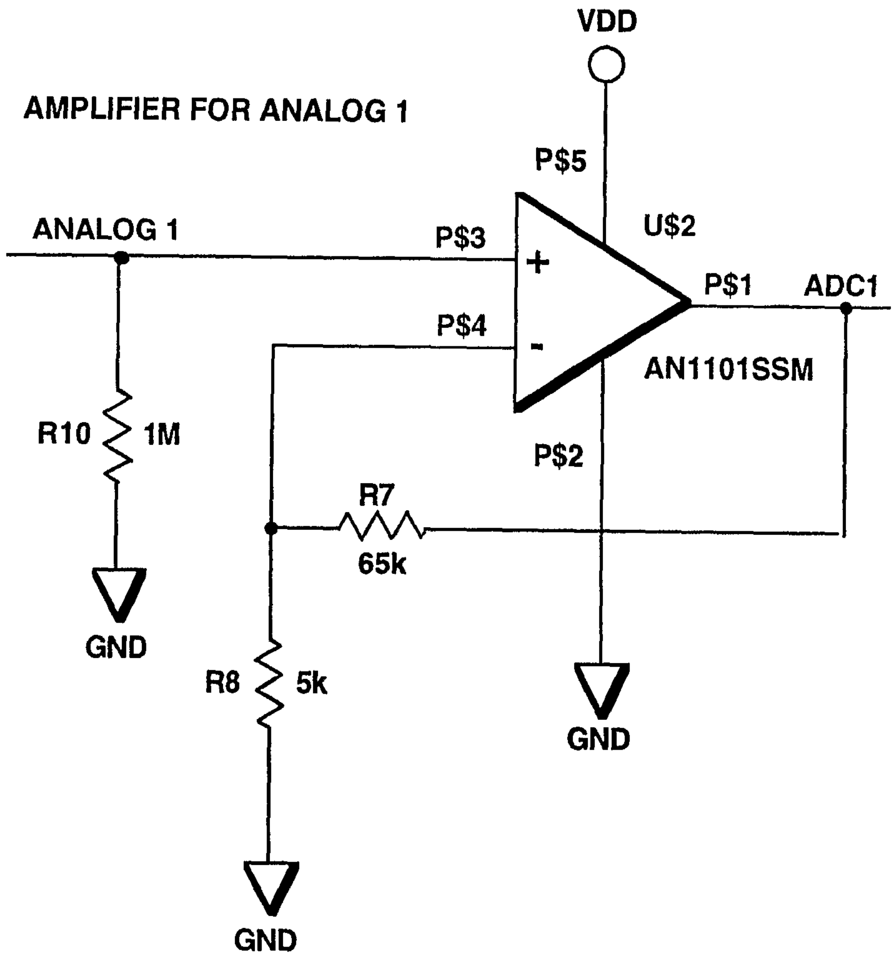

AMPLIFIER FOR ANALOG 1
VDD
P$5
U$2
ANALOG 1
P$3
+
P$1
ADC1
P$4
-
AN1101SSM
R10
1M
P$2
R7
65k
GND
R8
5k
GND
GND

Figure 7D

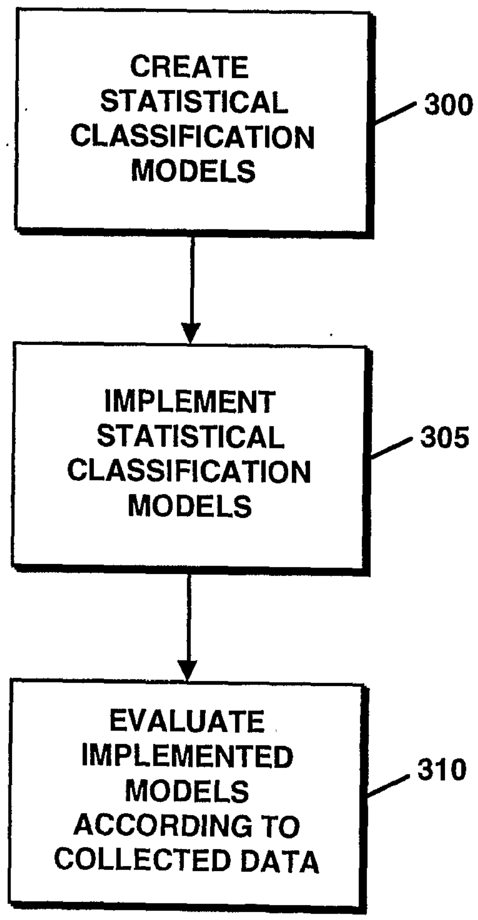

CREATE STATISTICAL CLASSIFICATION MODELS
300
IMPLEMENT STATISTICAL CLASSIFICATION MODELS
305
EVALUATE IMPLEMENTED MODELS ACCORDING TO COLLECTED DATA
310

Figure 8

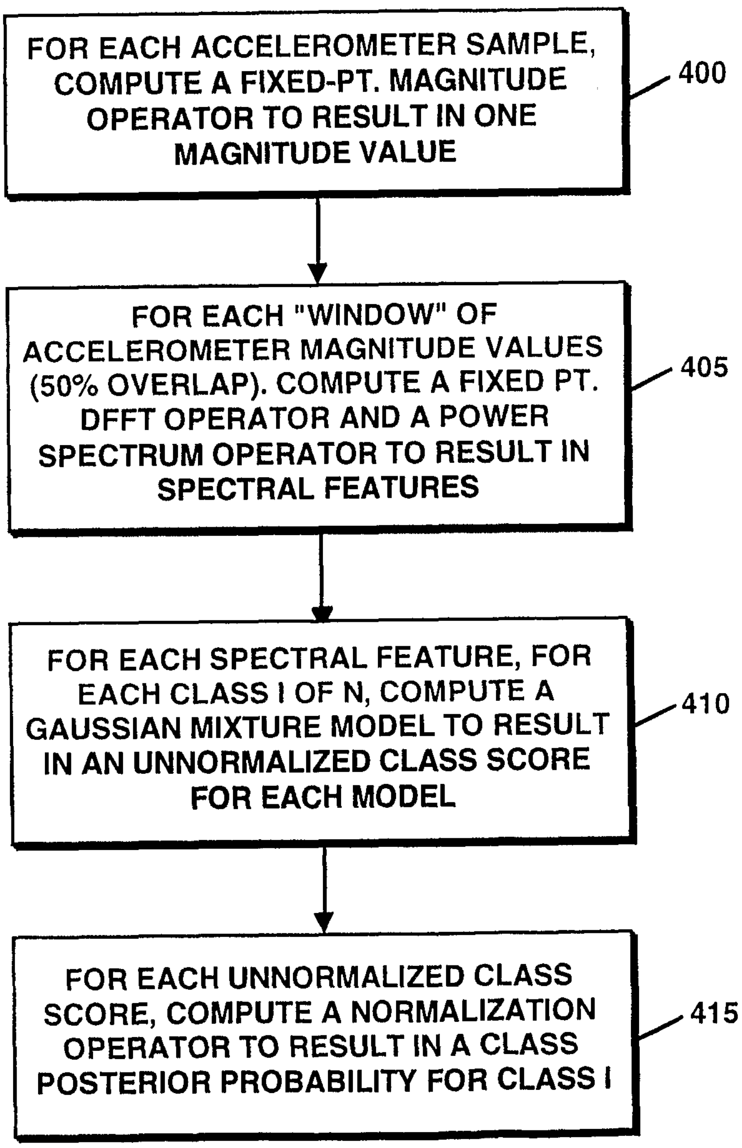

FOR EACH ACCELEROMETER SAMPLE, COMPUTE A FIXED-PT. MAGNITUDE OPERATOR TO RESULT IN ONE MAGNITUDE VALUE
400
FOR EACH "WINDOW" OF ACCELEROMETER MAGNITUDE VALUES (50% OVERLAP). COMPUTE A FIXED PT. DFFT OPERATOR AND A POWER SPECTRUM OPERATOR TO RESULT IN SPECTRAL FEATURES
405
FOR EACH SPECTRAL FEATURE, FOR EACH CLASS I OF N, COMPUTE A GAUSSIAN MIXTURE MODEL TO RESULT IN AN UNNORMALIZED CLASS SCORE FOR EACH MODEL
410
FOR EACH UNNORMALIZED CLASS SCORE, COMPUTE A NORMALIZATION OPERATOR TO RESULT IN A CLASS POSTERIOR PROBABILITY FOR CLASS I
415

Figure 9

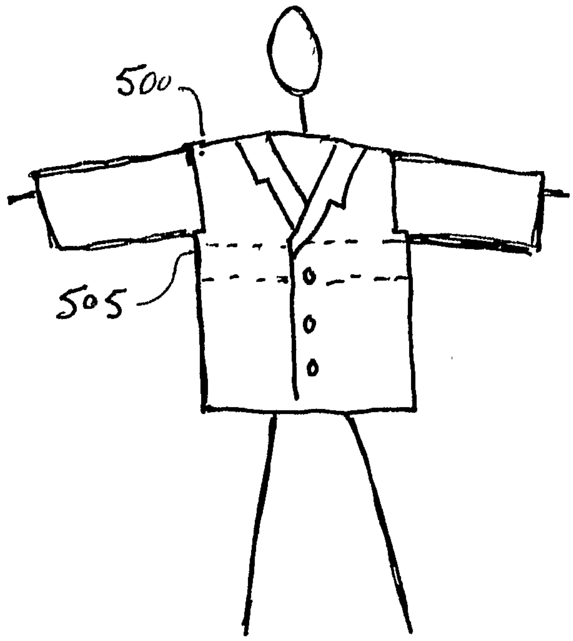


Figure 10

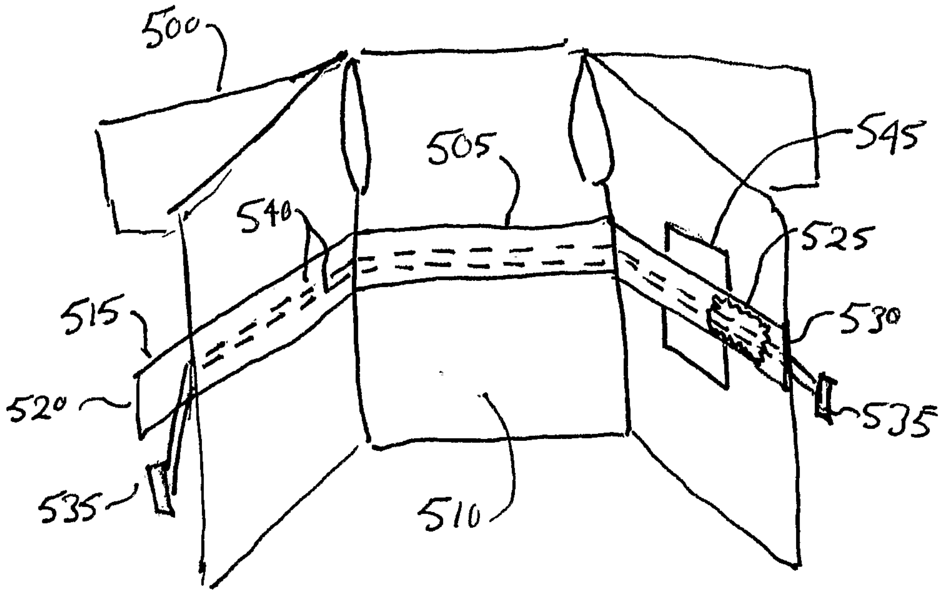


Figure 11

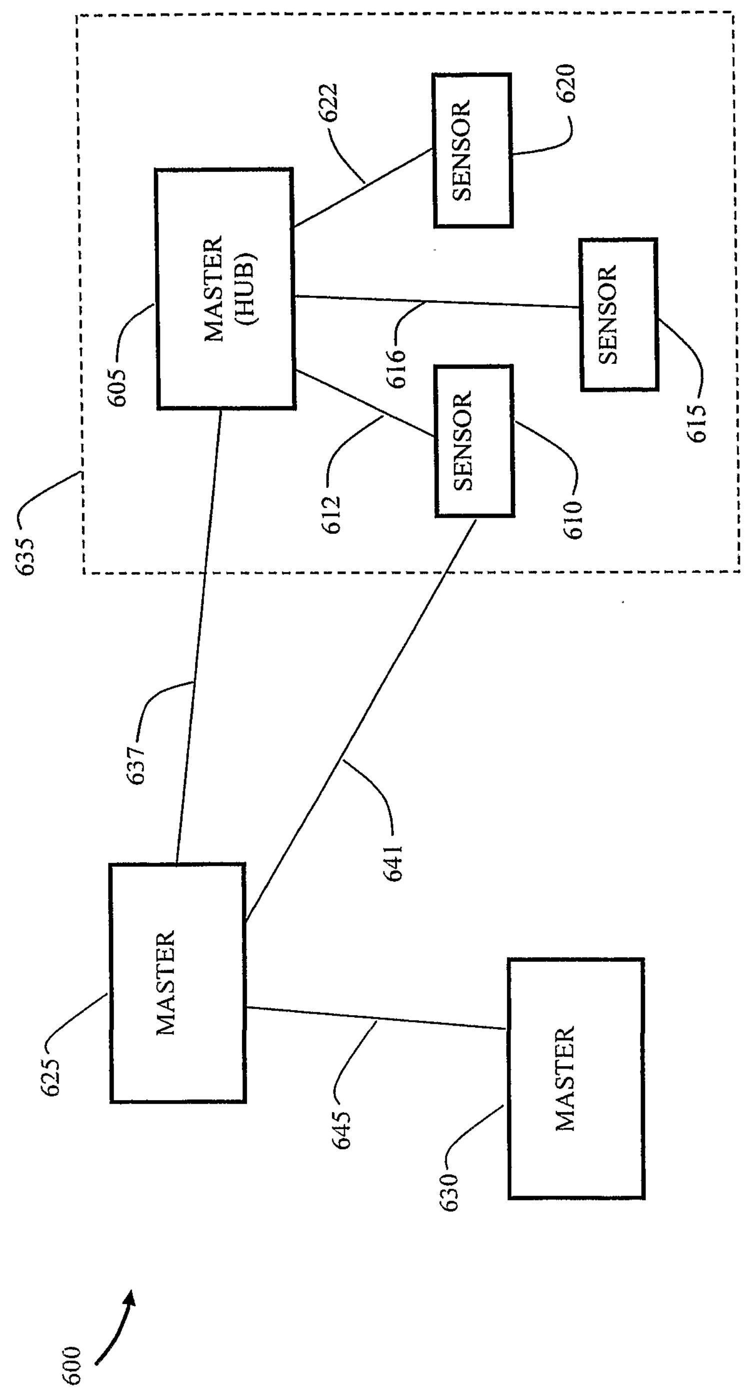

600
635
MASTER
(HUB)
605
622
SENSOR
620
SENSOR
615
616
SENSOR
612
610
637
641
MASTER
625
645
MASTER
630

FIGURE 12