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(54) ENERGY HARVESTING FOR WIRELESS SENSOR OPERATION AND DATA TRANSMISSION

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(60) Provisional application No. 60/362,432, filed on Mar. 7, 2002. Provisional application No. 60/443,120, filed on Jan. 28, 2003.

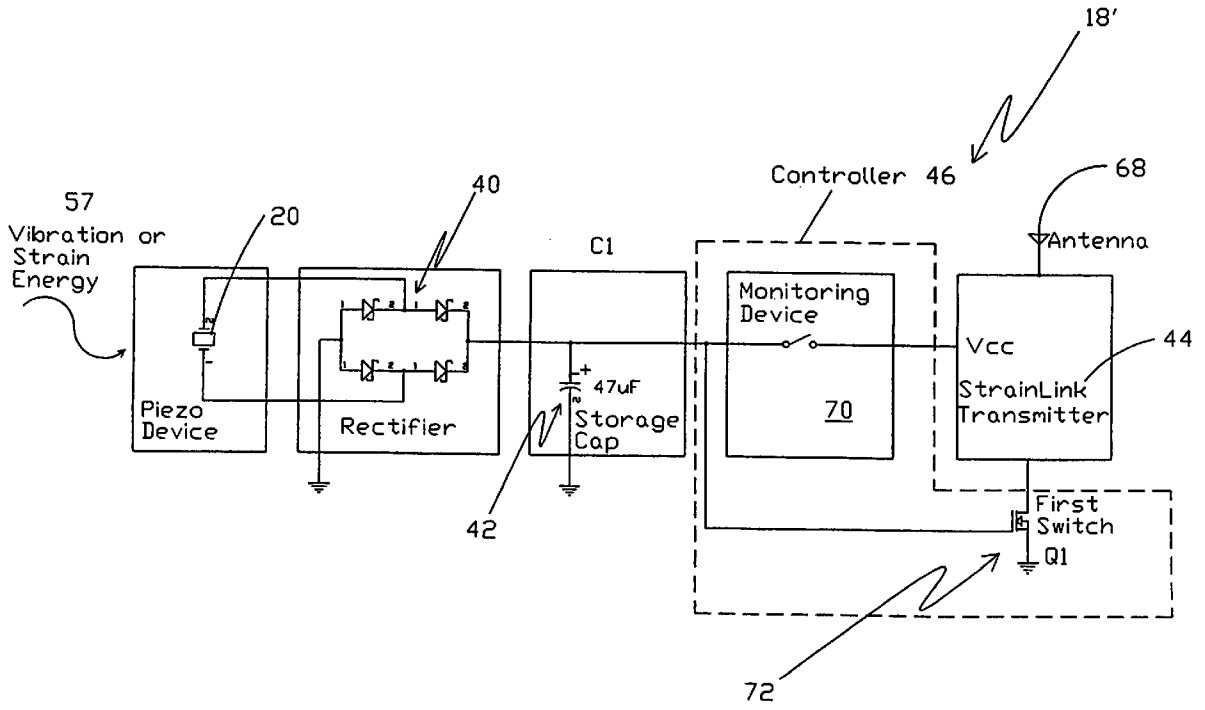
Publication Classification

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(57) **ABSTRACT**

A device for powering a load from an ambient source of energy is provided. The device includes an energy harvesting device for harvesting energy from the ambient source of energy wherein the rate energy is harvested from the ambient source of energy is below that required for directly powering the load. A storage device is connected to the energy harvesting device. The storage device receives electrical energy from the energy harvesting device and is for storing the electrical energy. A controller is connected to the storage device for monitoring the amount of electrical energy stored in the storage device and for switchably connecting the storage device to the load when the stored energy exceeds a first threshold. The system can be used for powering a sensor and for transmitting sensor data, such as tire pressure.



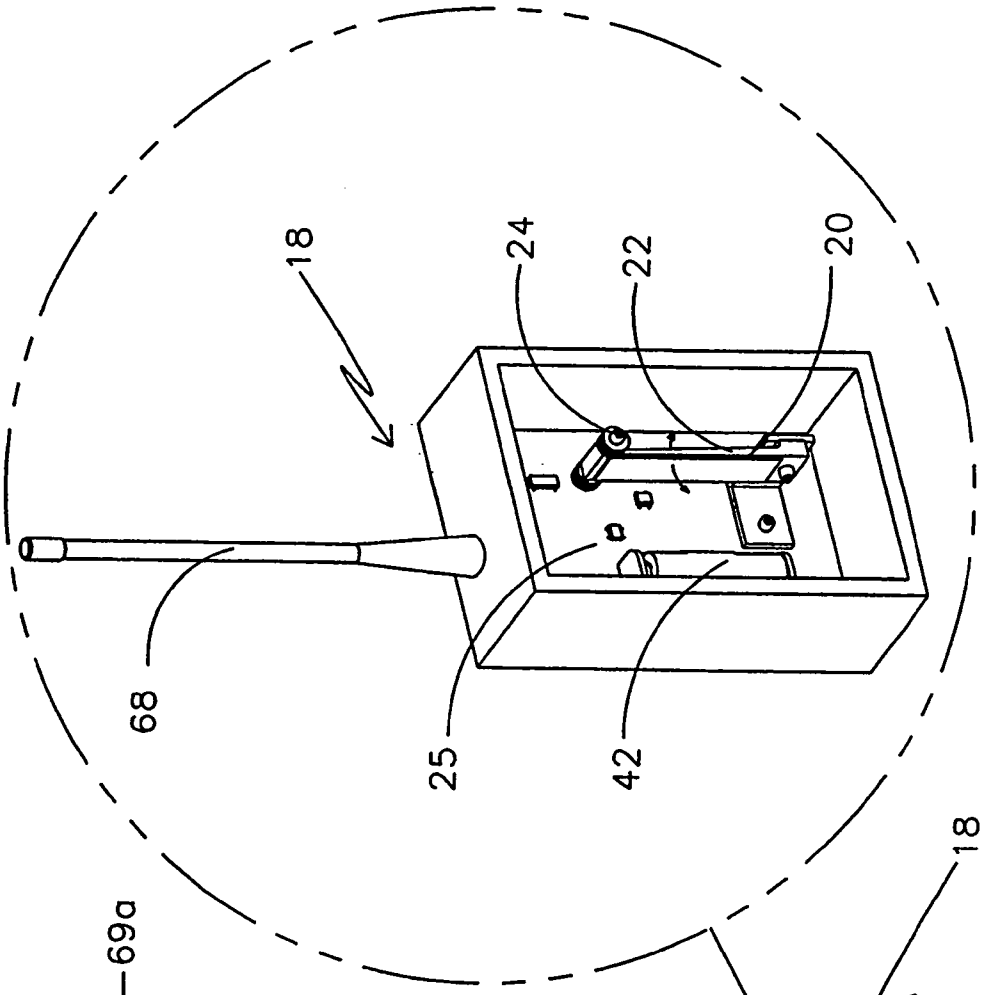


FIG. 1b

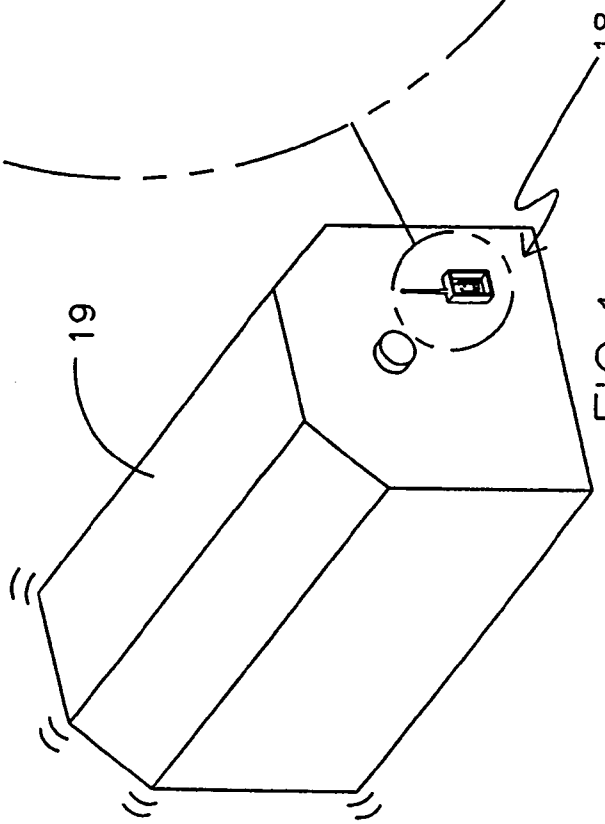


FIG. 1a

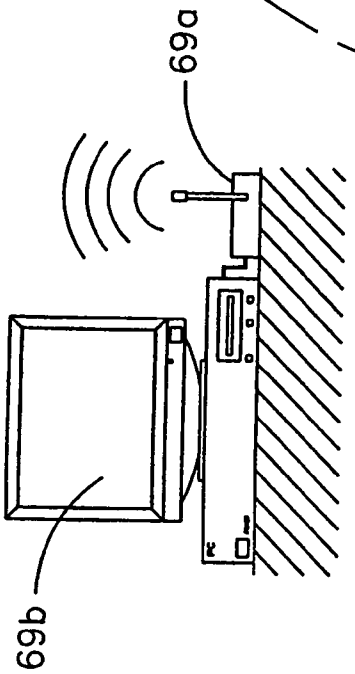


FIG. 1d

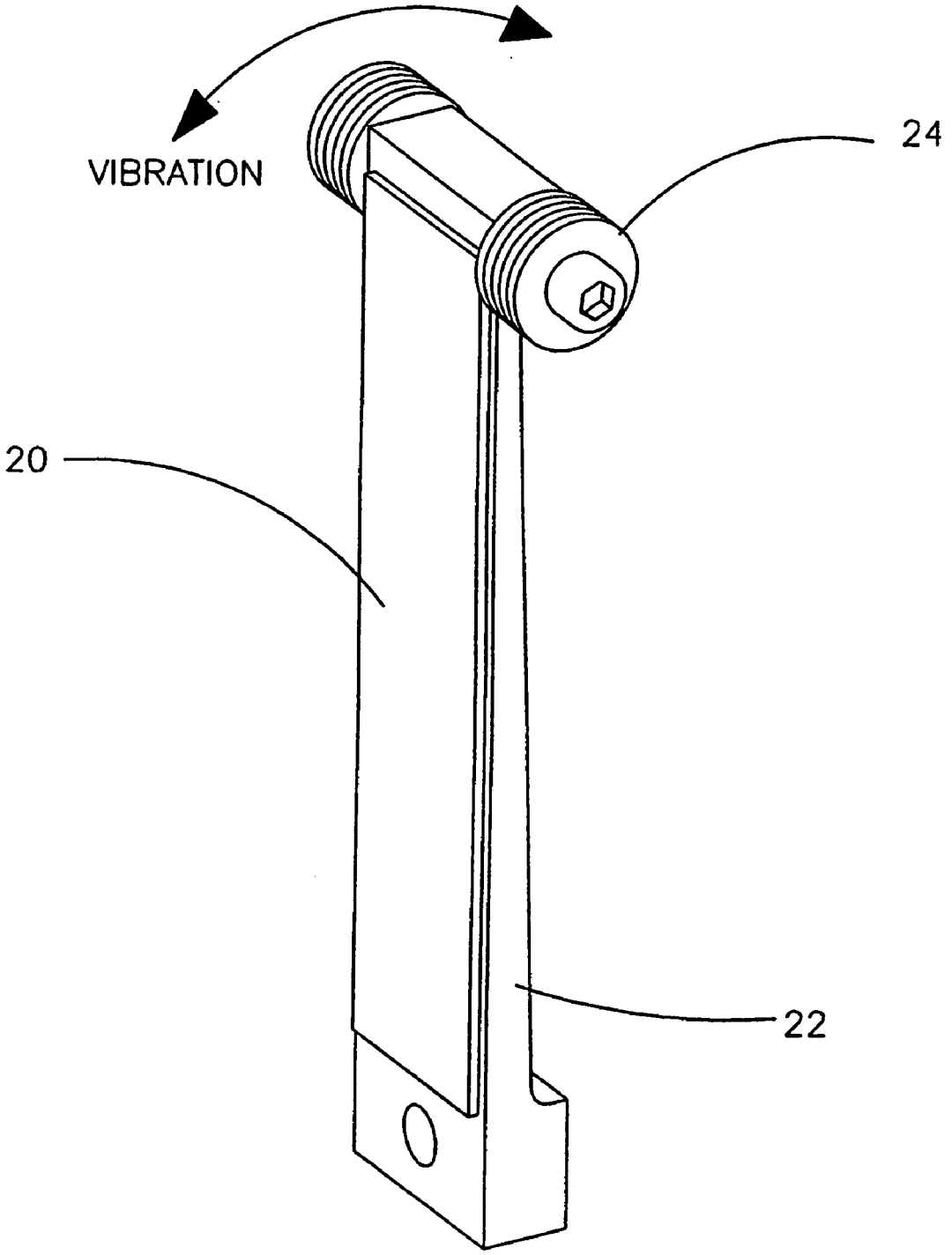


FIG. 1c

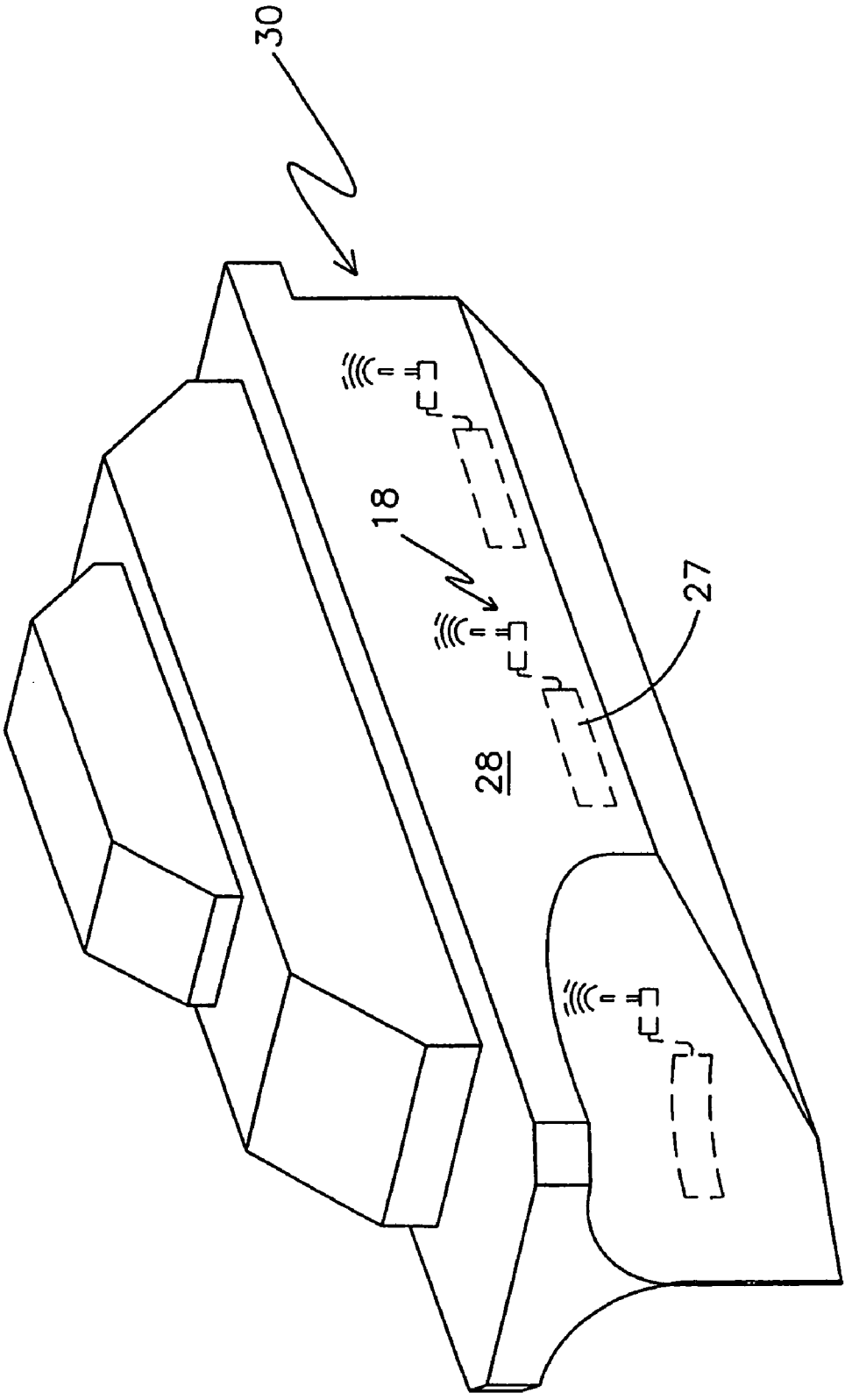


FIG. 2

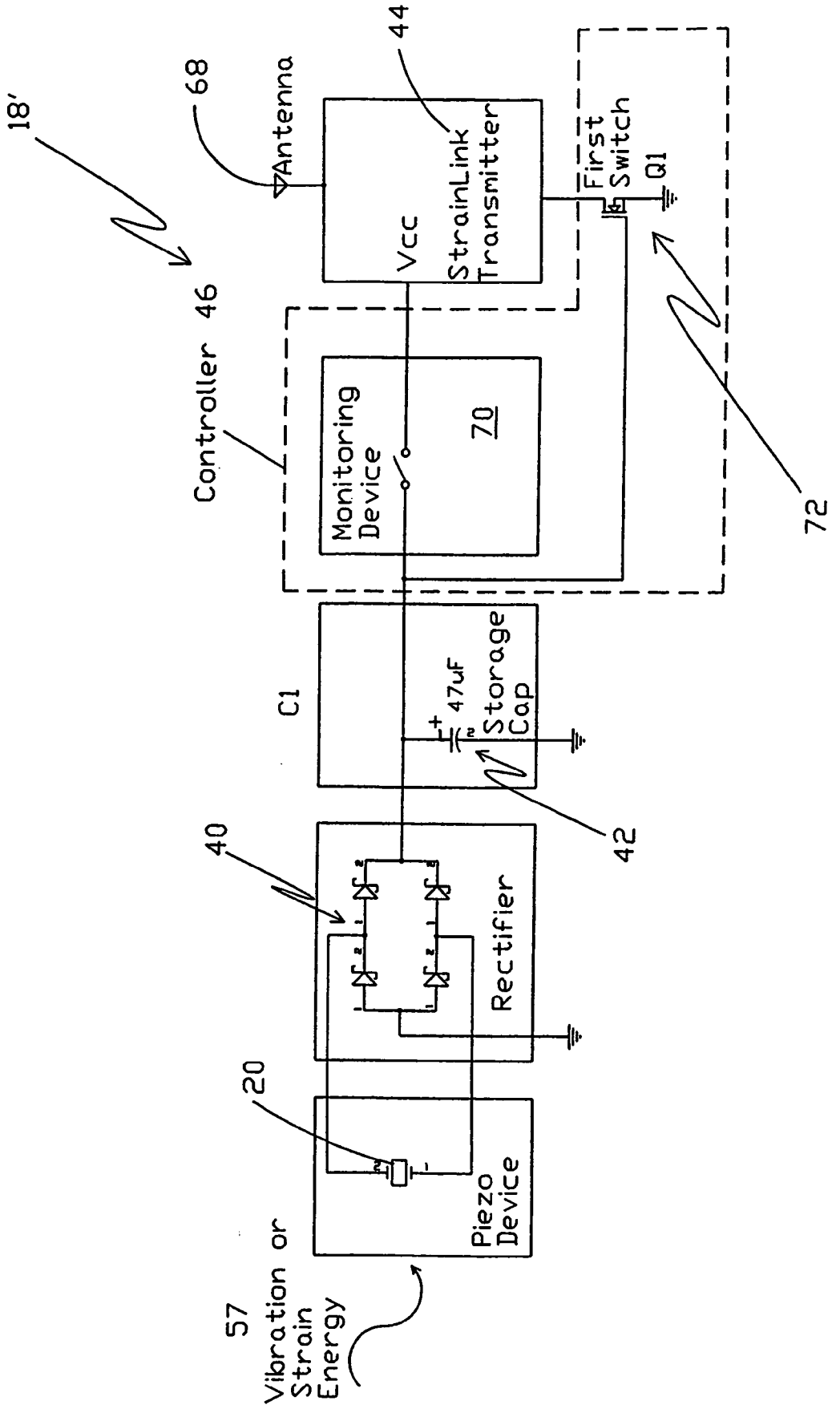

18'
68
Antenna
44
StrainLink Transmitter
Vcc
First Switch
Q1
Controller 46
Monitoring Device
70
72
C1
47uF
Storage Cap
42
40
Rectifier
20
Piezo Device
57
Vibration or Strain Energy

FIG. 3a

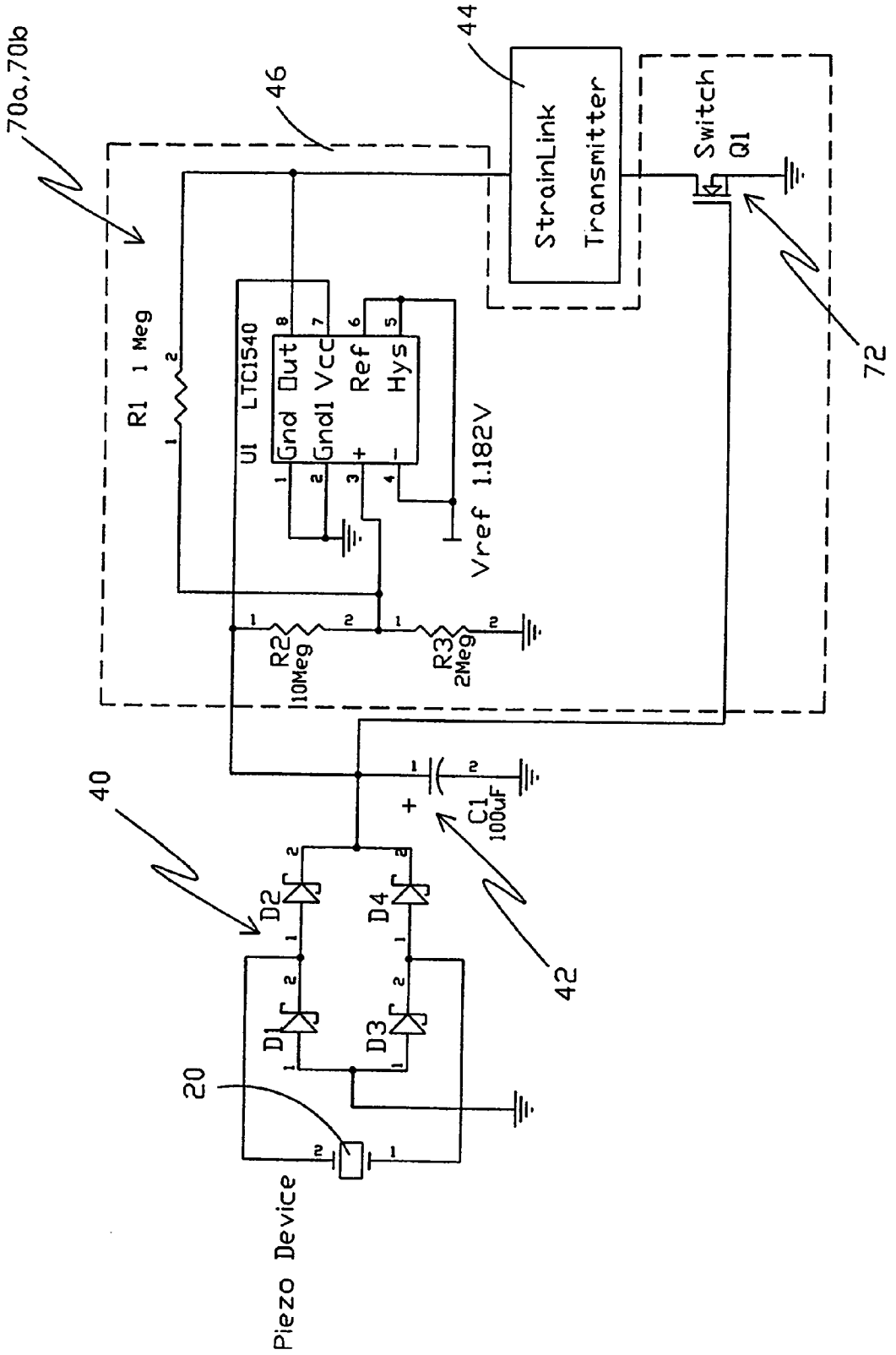

70a,70b
46
44
StrainLink
Transmitter
Switch
Q1
72
R1 1 Meg
U1 LTC1540
Gnd Out
Gnd Vcc
Ref
Hys
Vref 1.182V
R2
110Meg
R3
2Meg
C1
100uF
40
42
D2
D4
D1
D3
20
Piezo Device

FIG. 3b

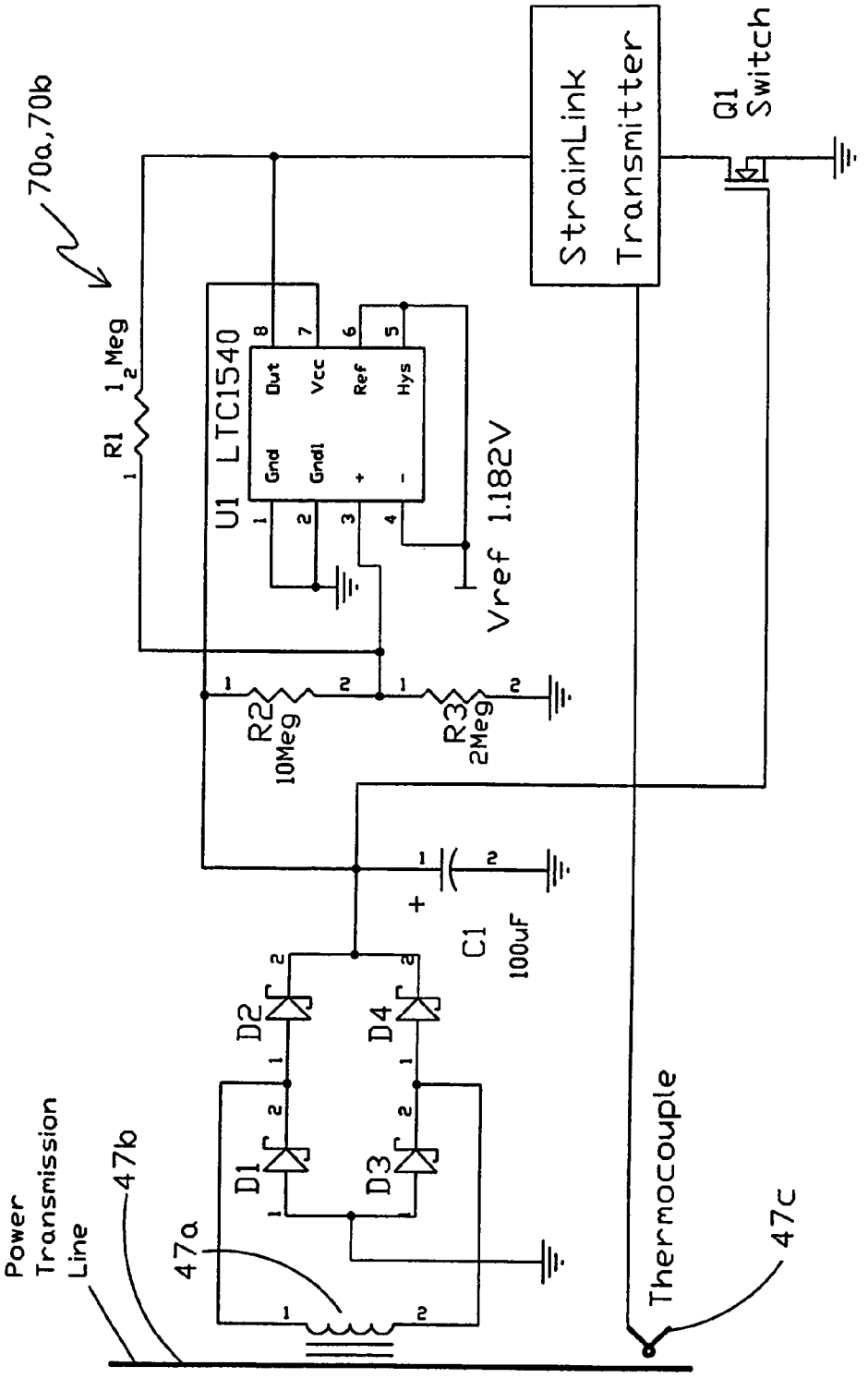

70a,70b
R1 1Meg
U1 LTC1540
Out
Vcc
Ref
Hys
Gnd
Gnd
Vref 1.182V
StrainLink Transmitter
Q1 Switch
R2 10Meg
R3 2Meg
C1 100uF
D1
D2
D3
D4
Power Transmission Line
47b
47a
Thermocouple
47c

FIG. 4

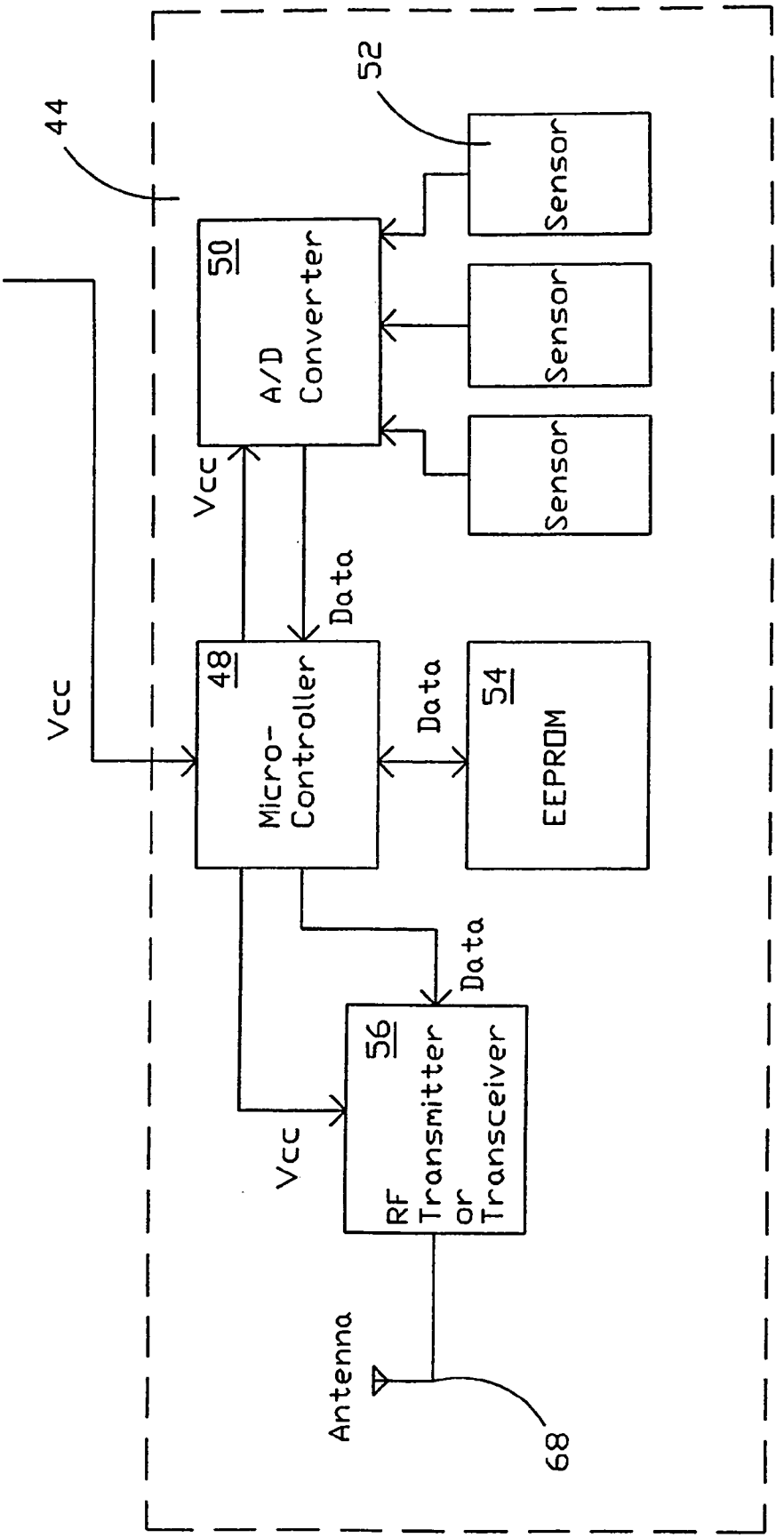

44
52
Sensor
Sensor
Sensor
50
A/D
Converter
Vcc
Data
Vcc
48
Micro-
Controller
Data
54
EEPROM
Data
56
RF
Transmitter
or
Transceiver
Vcc
Antenna
68

FIG. 5

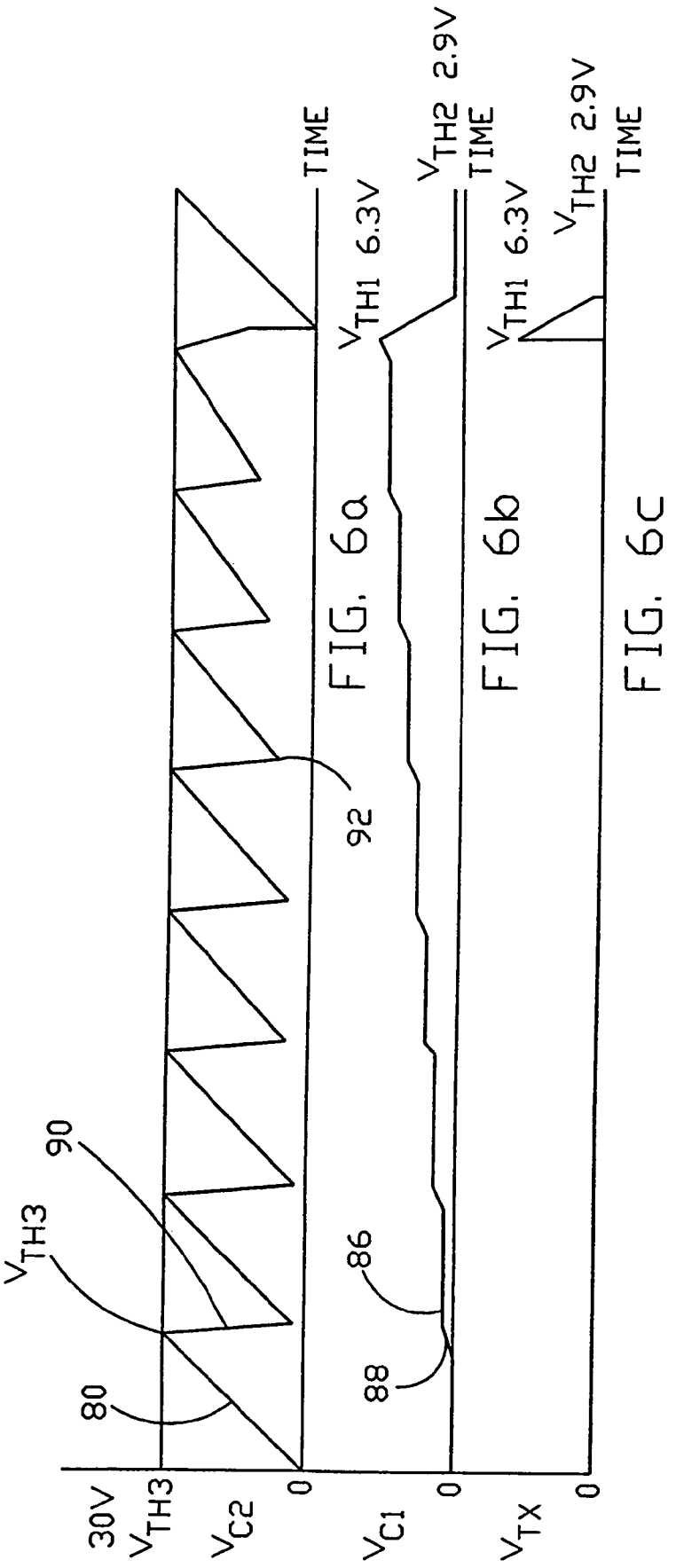


FIG. 6a

FIG. 6b

FIG. 6c

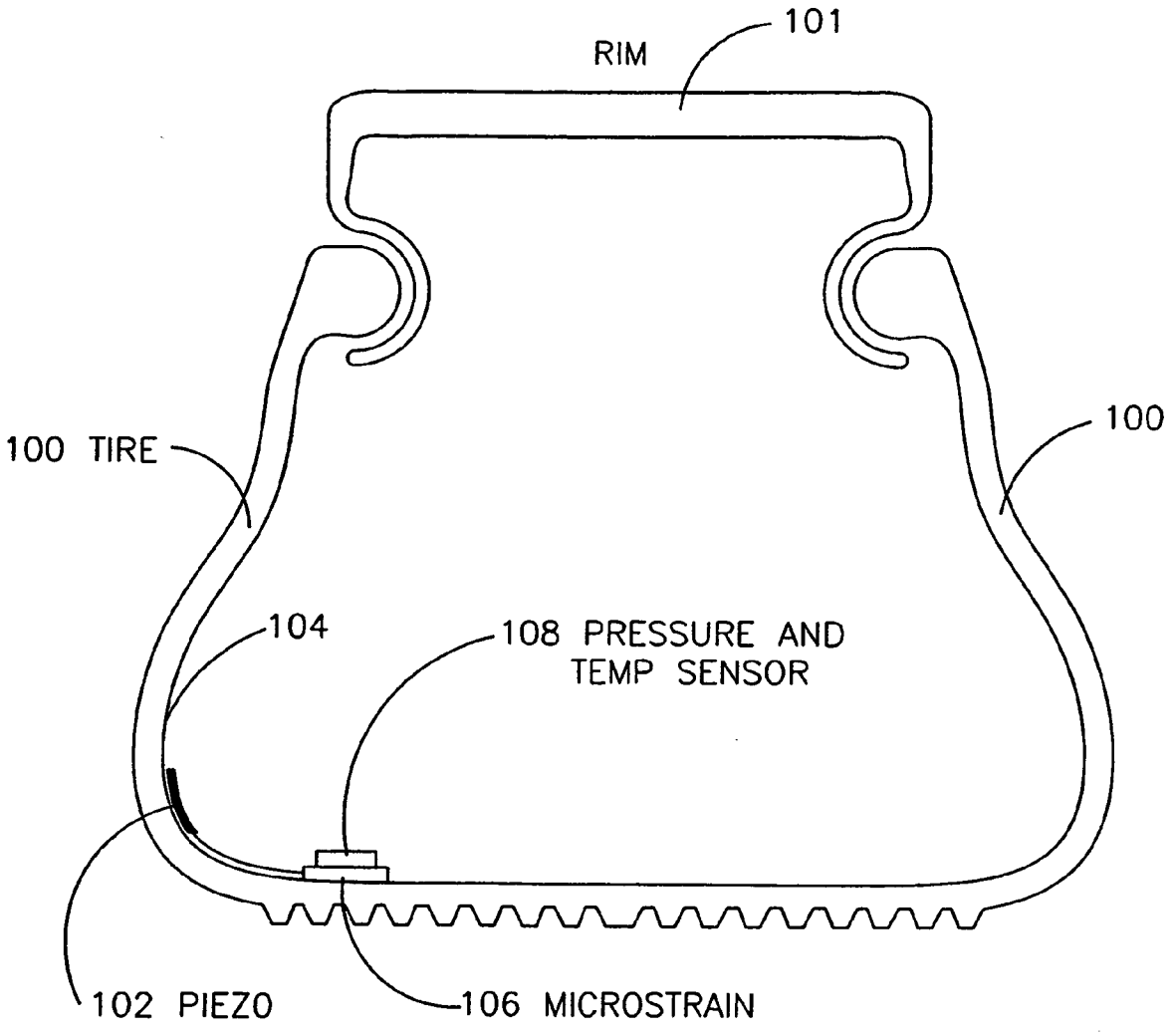

101
RIM
100 TIRE
100
104
108 PRESSURE AND
TEMP SENSOR
102 PIEZO
106 MICROSTRAIN

FIG. 7

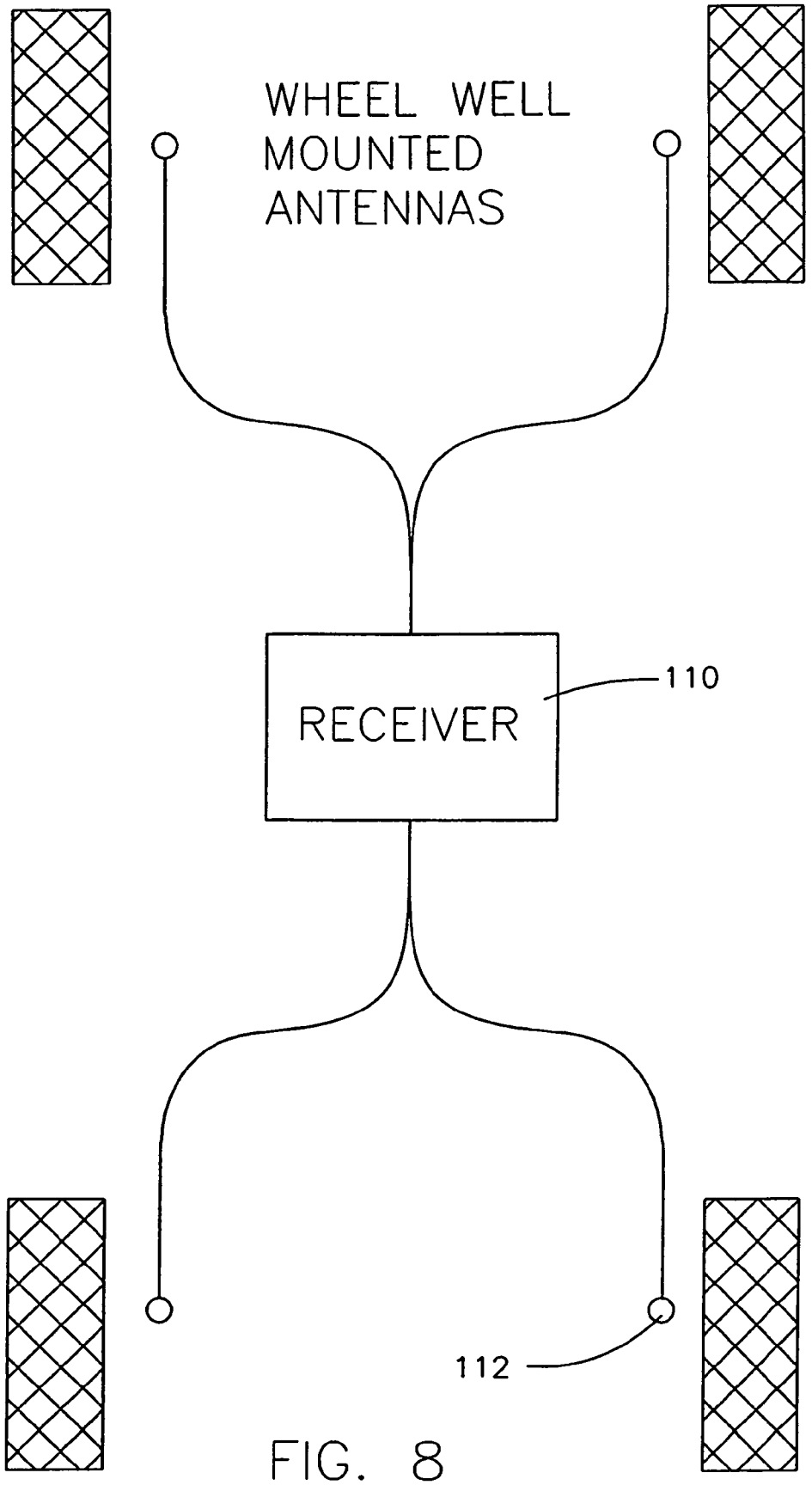


FIG. 8

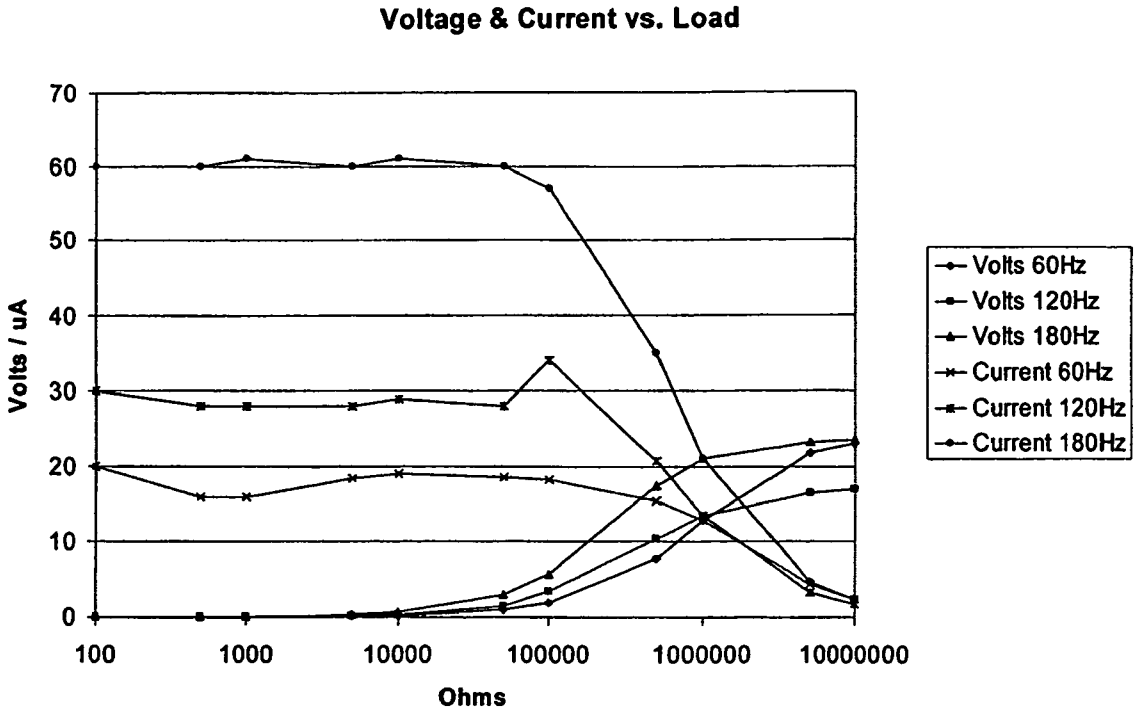

Voltage & Current vs. Load
Volts / uA
70
60
50
40
30
20
10
0
100
1000
10000
100000
1000000
10000000
Ohms
Volts 60Hz
Volts 120Hz
Volts 180Hz
Current 60Hz
Current 120Hz
Current 180Hz

FIG. 9

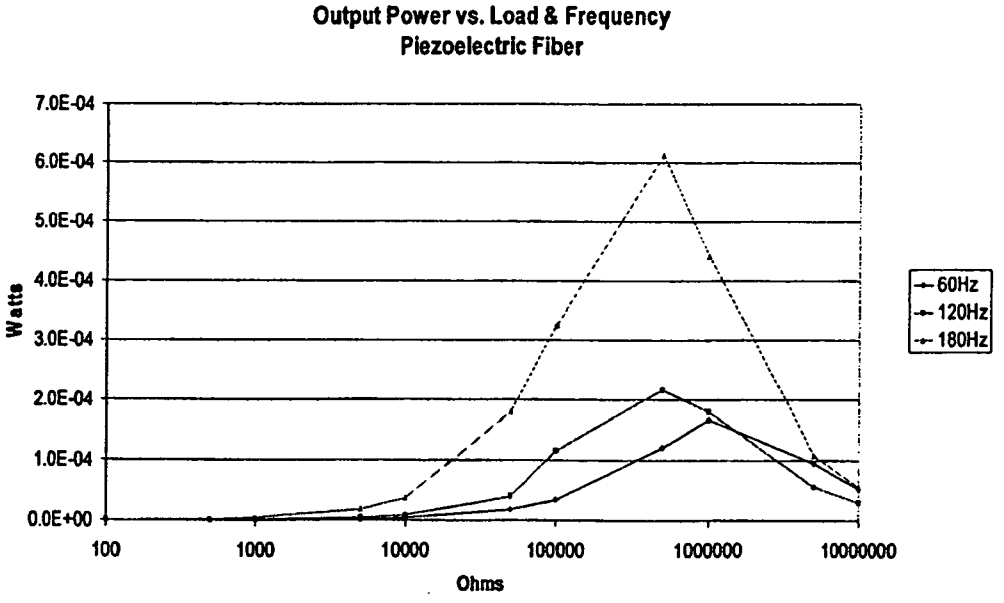
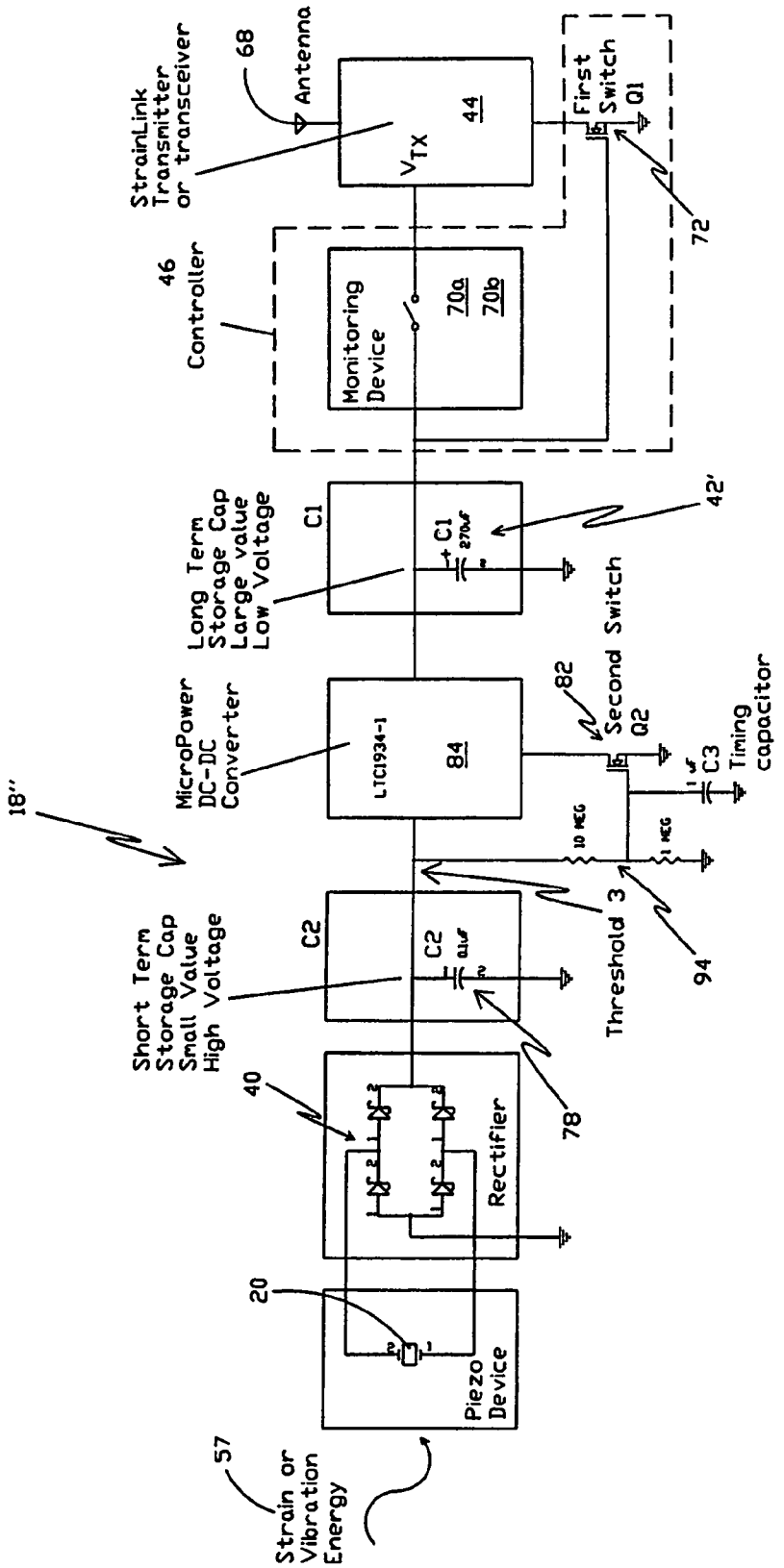

Output Power vs. Load & Frequency
Piezoelectric Fiber
Watts
7.0E-04
6.0E-04
5.0E-04
4.0E-04
3.0E-04
2.0E-04
1.0E-04
0.0E+00
100
1000
10000
100000
1000000
10000000
Ohms
60Hz
120Hz
180Hz

FIG. 10



1. C2 is charged to peak piezo voltage.
2. S2 enables converter at threshold 1.
3. Converter transforms high impedance charge in C2 to discharged C1.
4. When C1 is charged to threashold 2, controller connects transmitter or transceiver.
5. When charge in C1 is depleted below threashold volatge 3, controller disconnects load.

FIG. 11a

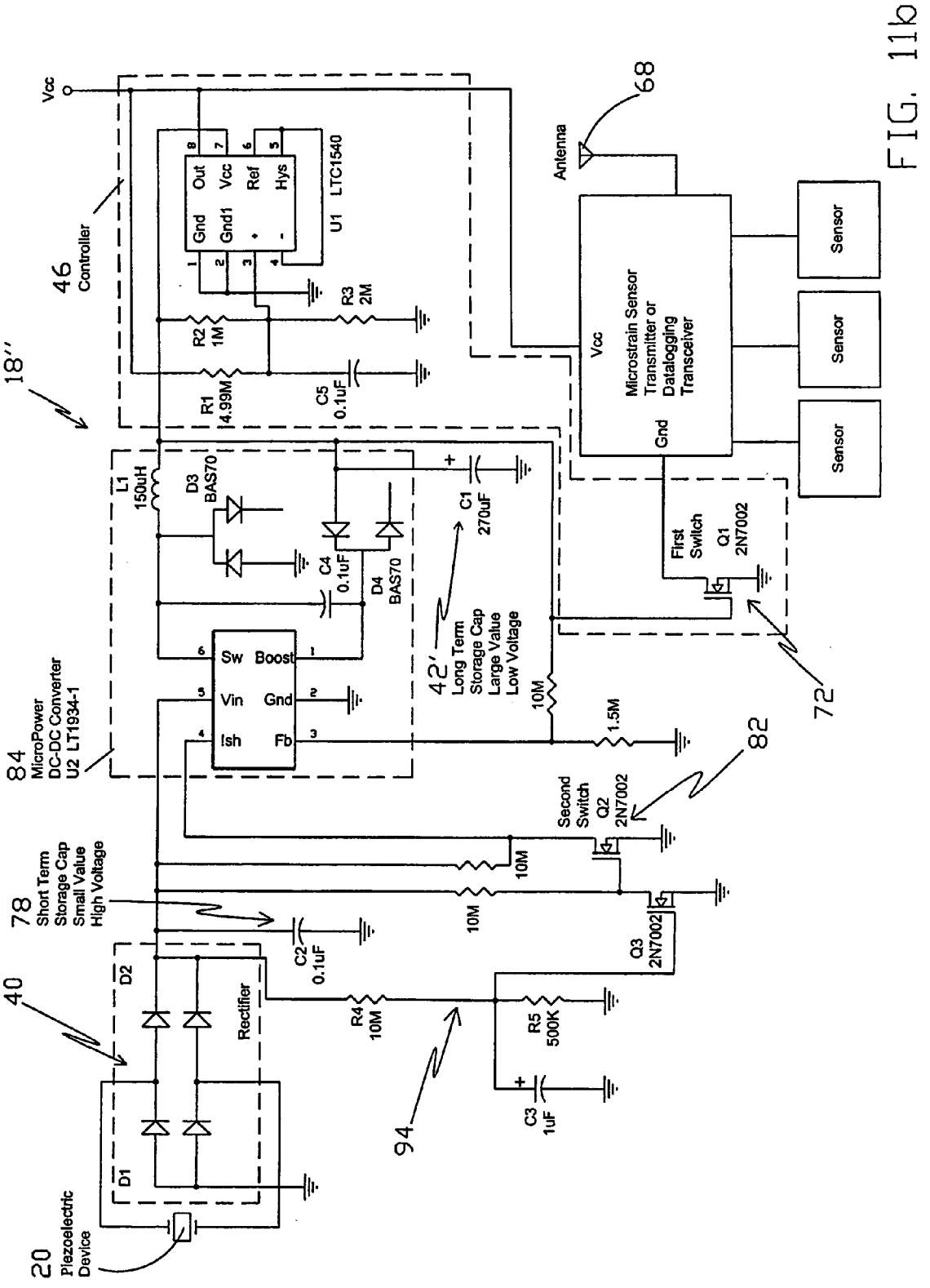

Vcc
46 Controller
U1 LTC1540
Out
Vcc
Ref
Hys
Gnd
Gnd1
R3 2M
R2 1M
R1 4.99M
C5 0.1uF
18''
68
Antenna
Microstrain Sensor Transmitter or Datalogging Transceiver
Vcc
Gnd
Sensor
Sensor
Sensor
L1 150uH
D3 BAS70
C4 0.1uF
D4 BAS70
C1 270uF
First Switch
Q1 2N7002
72
42' Long Term Storage Cap Large Value Low Voltage
84 MicroPower DC-DC Converter U2 LT1934-1
Sw
Boost
Vin
Gnd
Ish
Fb
10M
1.5M
82
Second Switch
Q2 2N7002
78 Short Term Storage Cap Small Value High Voltage
10M
10M
Q3 2N7002
C2 0.1uF
40
D2
Rectifier
R4 10M
R5 500K
94
C3 1uF
D1
20 Piezoelectric Device

FIG. 11b

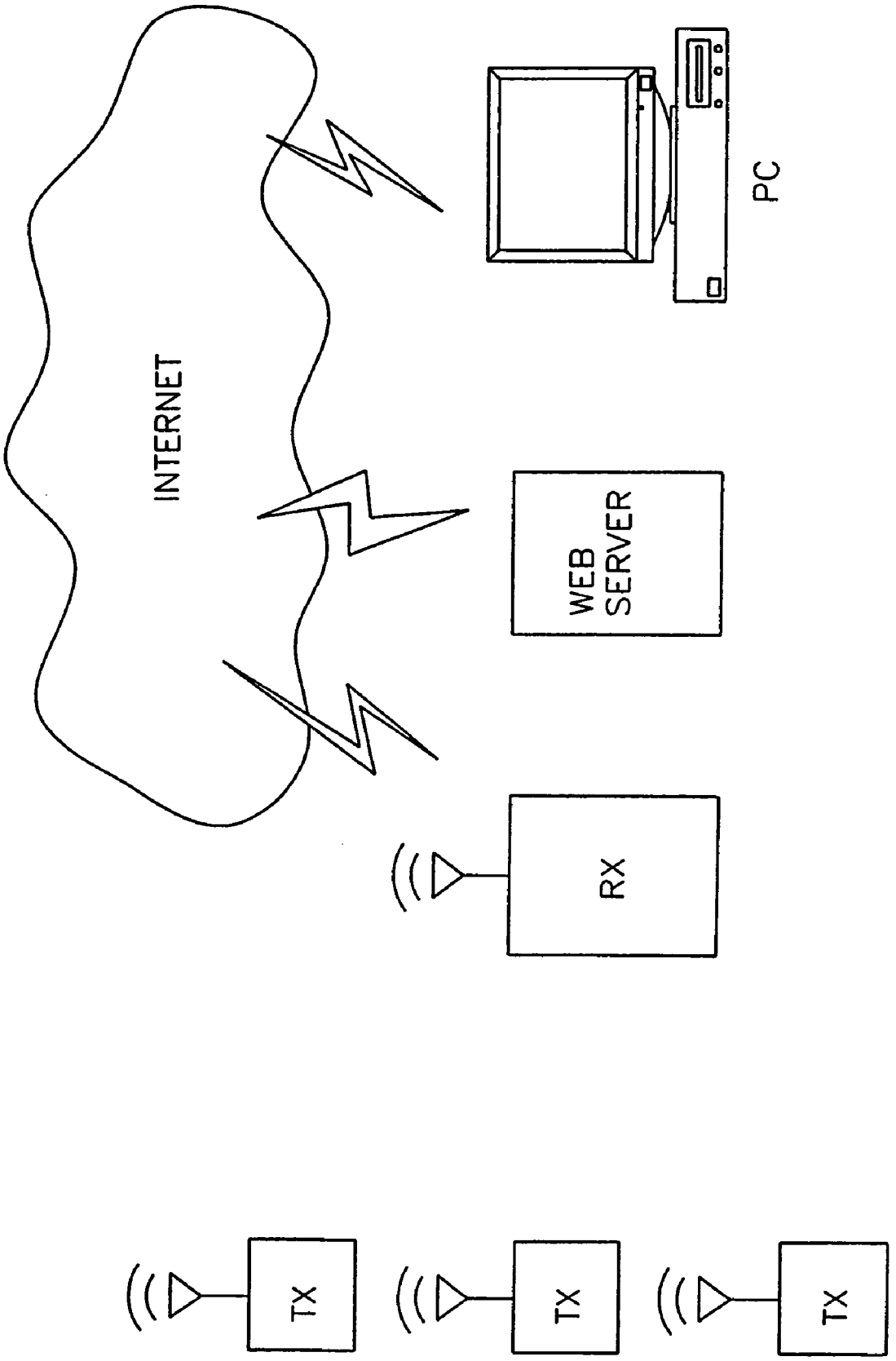


FIG. 12

ENERGY HARVESTING FOR WIRELESS SENSOR OPERATION AND DATA TRANSMISSION

RELATED APPLICATIONS

[0001] This patent application is a divisional of U.S. patent application Ser. No. 10/379,223, incorporated herein by reference, and claims benefit of provisional patent application 60/362,432, filed Mar. 7, 2002, incorporated herein by reference and provisional patent application 60/443,120, filed Jan. 28, 2003, incorporated herein by reference. This patent application is related to the following U.S. patent applications:

[0002] Ser. No. 09/731,066, docket number 1024-034, filed Dec. 6, 2000, incorporated herein by reference;

[0003] Ser. No. 09/757,909, docket number 1024-035, filed Jan. 10, 2001, incorporated herein by reference;

[0004] Ser. No. 09/801,230, docket number 1024-036, filed Mar. 7, 2001, incorporated herein by reference;

[0005] Ser. No. 09/768,858, docket number 1024-037, filed Jan. 24, 2001, incorporated herein by reference;

[0006] Ser. No. 09/114,106, docket number 1024-041, filed Jul. 11, 1998, incorporated herein by reference;

[0007] Ser. No. 09/457,493, docket number 1024-045, filed Dec. 8, 1999, incorporated herein by reference; and

[0008] non-provisional patent application having docket number 115-004, Ser. No. 10/379,224, filed the same day as this application, incorporated herein by reference.

FIELD OF THE INVENTION

[0009] This invention generally relates to collecting and transmitting data. More particularly, it relates to a device for sensing, storing and transmitting data. Even more particularly, it relates to a device that can that can be attached to a structure or live subject and that can harvest energy from its environment to power sensing, storing and transmitting data about the structure or live subject.

BACKGROUND OF THE INVENTION

[0010] Several available devices convert mechanical energy in the local environment into electrical energy, including the Seiko "Kinetic" watch and mechanical wind-up radios. An article, "Energy Scavenging with Shoe-Mounted Piezoelectrics," by N. S. Shenck and J. A Paradiso http:/computer.org/micro/homepage/may_june/shenck/index.htm, reports on systems that capture energy from the user's environment to provide electricity to wearable microelectronic devices without batteries. The unobtrusive devices scavenge electricity from the forces exerted on a shoe during walking. The devices include a flexible piezoelectric foil stave to harness sole-bending energy and a reinforced piezoelectric dimorph to capture heel-strike energy. They also report on prototype development of radio frequency identification (RFID) tags which are self powered by a pair of sneakers.6 A recent report by Meniger et al., entitled "Vibration-to-Energy Conversion", discloses a microelectromechanical system (MEMs) device for the conversion of ambient mechanical vibration into electrical energy through the use of a variable capacitor http://www.kric.ac.kr:8080/pubs/articles/proceedings/dac/313817/p48-meninger/p48-men inger.pdf. However, these MEMs systems only demonstrated 8 microwatts of power. Transmission of RF data over distances of 20 feet or more requires milliwatt power levels.

[0011] Low power sensors have been developed, as described on commonly assigned U.S. patent application Ser. No. 09/731,066, to Arms, that includes a sensing unit for attaching to a structure or live subject for sensing a parameter of the structure or live subject. The sensing unit includes a sensor, a data storage device, and a transmitting device. The data storage device is for storing data from the sensor. Power is provided by a power supply such as a rechargeable battery or fuel cell. The rechargeable battery can be recharged by inductive coupling from an external control unit.

[0012] Over the past years, sensors, signal conditioners, processors, and digital wireless radio frequency (RF) links have become smaller, consumed less power, and included higher levels of integration. The Ser. No. 09/731,066 application, for example, provides sensing, acquisition, storage, and reporting functions. Wireless networks coupled with intelligent sensors and distributed computing have enabled a new paradigm of machine monitoring.

[0013] A paper, "Wireless Inductive Robotic Inspection of Structures," by Esser, et al, proceedings of the IASTED International Conference, Robotics and Applications 2000, Aug. 14-16, 2000, Honolulu, Hi., describes an autonomous robotic structural inspection system capable of remote powering and data collection from a network of embedded sensing nodes and providing remote data access via the internet. The system uses microminiature, multichannel, wireless programmable addressable sensing modules to sample data from a variety of sensors. The nodes are inductively powered, eliminating the need for batteries or interconnecting lead wires.

[0014] Wireless sensors have the advantage of eliminating the cost of installing wiring. They also improve reliability by eliminating connector problems. However, wireless sensors still require system power in order to operate. If power outages occur, critical data collected by the sensors may be lost. In some cases, sensors may be hardwired to a vehicle's power system. In other cases however, the need to hard wire to a power system defeats the advantages of wireless sensors, and this may be unacceptable for many applications. Most prior wireless structural monitoring systems have therefore relied on continuous power supplied by batteries. For example, in 1972, Weiss developed a battery powered inductive strain measurement system, which measured and counted strain levels for aircraft fatigue. Traditional batteries, however, become depleted and must be periodically replaced or recharged, adding an additional maintenance task that must be performed. This is particularly a problem for monitors used for a condition based maintenance program since it adds additional maintenance for the condition based monitoring system itself.

[0015] None of the systems for sensing changes in the environment have collected available mechanical energy to provide the electricity for running the sensors, storing data from the sensor, or communicating the data externally. Thus, a better system for powering sensors and storage devices, and for transmitting data gathered by sensors is needed, and this solution is provided by the following invention.

SUMMARY OF THE INVENTION

[0016] It is therefore an object of the present invention to provide a scheme for powering a wireless sensor system with a source of energy that avoids the need to provide, replace or recharge batteries;

[0017] It is a further object of the present invention to provide a scheme for powering a load with energy harvested from an ambient source of energy in the local area, wherein the rate at which energy is harvested from the ambient source of energy is below that required for directly powering the load.

[0018] It is a further object of the present invention to provide a scheme for powering a sensor system with ambient mechanical energy collected from the environment of the sensor system or with energy obtained from ambient magnetic field coupled energy;

[0019] It is a further object of the present invention to provide a network of sensor systems in which sensors on the network are powered with ambient energy collected from the environment;

[0020] It is a further object of the present invention to provide a device for monitoring the health of a machine or another system in which the monitoring device is powered with ambient energy harvested from the environment.

[0021] It is a further object of the present invention to provide a sensing system that includes a sensor that is read with electrical energy obtained from the harvested mechanical energy;

[0022] It is a further object of the present invention to provide a wireless transmitter connected to receive and transmit information obtained by the sensor, in which the wireless transmitter is powered with electrical energy obtained from the harvested mechanical energy;

[0023] It is a feature of the present invention that a sensing system includes a component for harvesting ambient mechanical or magnetic energy and converts this energy into electrical energy;

[0024] It is a feature of the present invention to provide a data collection device that is powered by the electrical energy obtained from the harvested mechanical energy;

[0025] It is an advantage of the present invention that the data collection device can provide information about the environment using energy harvested from the environment; and

[0026] It is a further advantage of the present invention that the data collection device does not itself require maintenance for replacing or recharging batteries.

[0027] These and other objects, features, and advantages of the invention are accomplished by a device for powering a load from an ambient source of energy. The device comprises an energy harvesting device for harvesting energy from the ambient source of energy wherein the rate energy is harvested from the ambient source of energy is below that required for directly powering the load. A storage device is connected to the energy harvesting device. The storage device receives electrical energy from the energy harvesting device and is for storing the electrical energy. A controller is connected to the storage device is for monitoring the amount of electrical energy stored in the storage device and for switchably connecting the storage device to the load when the stored energy exceeds a first threshold.

[0028] Another aspect of the invention is an energy harvesting system comprising a piezoelectric transducer and a rectifier. The system also includes a reactive device having a high impedance approximately matching impedance of the piezoelectric transducer at its operating frequency for efficiently transferring energy from the piezoelectric transducer to the reactive device. The system also includes a low impedance high capacity storage device. The system also includes a circuit for monitoring voltage across the reactive device, and for transferring the charge from the reactive device to the low impedance high capacity storage device when the voltage across the reactive device reaches a specified voltage value.

[0029] Another aspect of the invention is a device for sensing temperature or pressure in a tire. The device includes a tire and a PZT mounted on the tire. The device also includes a circuit for harvesting energy from the PZT, wherein the circuit comprises an element having an impedance approximately matching impedance of the PZT. The device also includes a sensing module connected to the circuit, the sensing module including a sensor and a circuit for wirelessly transmitting sensor information.

BRIEF DESCRIPTION OF THE DRAWINGS

[0030] The foregoing and other objects, features, and advantages of the invention will be apparent from the following detailed description of the invention, as illustrated in the accompanying drawings, in which:

[0031] **FIG. 1***a* is a perspective view of an energy harvesting addressable wireless sensing node of the present invention mounted on a machine or structure;

[0032] **FIG. 1***b* is a perspective view of components within the energy harvesting addressable wireless sensing node;

[0033] **FIG. 1***c* is a perspective view of the energy harvesting cantilever shown in **FIG. 1***b* with variable mass for tuning to a vibration frequency of the machine or structure;

[0034] **FIG. 1***d* is a schematic diagram of a base station for receiving said wirelessly transmitted information;

[0035] **FIG. 2** is an alternative embodiment in which a large sheet of PZT fiber is embedded in material, such as a hull of ship so vibration or strain energy transmitted through the hull can be harvested;

[0036] **FIG. 3***a*, **3***b* are block diagrams of one embodiment of an energy harvesting addressable wireless sensing node of the present invention in which energy is harvested by a PZT;

[0037] **FIG. 4** is a block diagram of an alternate embodiment of an energy harvesting addressable wireless sensing

node of the present invention in which energy is harvested from a power transmission line;

[0038] **FIG. 5** is a block diagram of the wireless sensing module shown in **FIGS. 3***a*, **3***b*;

[0039] **FIG. 6***a* is a timing diagram of voltage across capacitor C2 of **FIG. 11**;

[0040] **FIG. 6***b* is a timing diagram of voltage across capacitor C1 of **FIG. 11**;

[0041] **FIG. 6***c* is a timing diagram of voltage across the transmitter of **FIG. 11** showing how charge gradually stored in long term storage capacitor C1 is used to briefly power the transmitter or transceiver;

[0042] **FIG. 7** is a cross sectional view of a tire having an energy harvesting device of the present invention to power transmitting pressure and temperature sense data;

[0043] **FIG. 8** is a schematic diagram showing a receiver mounted in a vehicle that receives signals indicating tire sensor data transmitted by each of the tires on the vehicle;

[0044] **FIG. 9** is a diagram showing data from an experimental test showing that the PZT provided the same low current output as load resistance was varied from 100 ohms to 50 Kohms;

[0045] **FIG. 10** is a diagram showing data from the experimental test showing that the optimum load impedance, that delivers maximum power, was found to be about 500 Kohms;

[0046] **FIG. 11***a* is a block diagram of an improved embodiment of an energy harvesting addressable wireless sensing node of the present invention having an additional stage of charge storage, monitoring, switching, and impedance conversion between the rectifier and the controller of **FIG. 3***a*;

[0047] **FIG. 11***b* is a schematic diagram showing more detail than the block diagram of **FIG. 11***a*; and

[0048] **FIG. 12** is a schematic diagram showing a wireless web enabled sensor network (WWSN) system that requires very little power.

DETAILED DESCRIPTION OF THE INVENTION

[0049] The present inventors recognized that substantial efficiency in collecting, storing, and transmitting data from wireless sensors could be provided by harvesting energy from the environment.

[0050] This invention is aimed at developing a new class of sensing systems that can wirelessly report data without the need for maintaining or replacing batteries. Instead, the sensing systems rely on harvesting vibration, strain energy, or magnetic coupled energy from the local environment for conversion to electrical power for storage and use to collect, store, or transmit data by the sensing system. Thus, machines, structures, and live subjects can be monitored without the need for replacing or recharging batteries or for a battery maintenance schedule. Truly smart structures and machines will thus be able to autonomously report their condition throughout their operating life without the mechanism used for reporting the data itself requiring maintenance. The system can be used to run and communicate with actuators as well as sensors.

[0051] One important use of the present invention is to improve traditional condition based maintenance. Condition based maintenance provides a more accurate and cost effective maintenance program for equipment or structures. The present invention reduces unnecessary preventive maintenance for the devices used to monitor. In addition to providing for wireless communication without batteries, the present invention provides the components necessary to realize the potential benefits of condition based monitoring, including information acquisition, analysis, storage, and reporting technologies that substantially lower power requirements, making energy harvesting for condition based maintenance a realistic source of energy.

[0052] An illustration of condition based maintenance and another important use for the present invention is aboard ships where batteryless sensing systems may be used for wirelessly monitoring oil debris or oil condition, tank & hull corrosion, combustion pressure, water-lubricated-bearing wear, and machine condition. The invention can also be used for integrated, hierarchical machinery diagnostics & prognostics; machinery diagnostics & prognostics; open systems architecture condition based maintenance; human—computer interface condition based maintenance; and diagnostic of insulation, such as wire and windings. The invention can also be used on land vehicles or aircraft for purposes such as to monitor and report tire temperature and pressure. In each case mechanical energy, such as the energy of vibration of the vehicle, can be used to power the sensor and its storage or communications apparatus.

[0053] Batteries, and the additional maintenance burden for replacing or recharging batteries, are avoided in the present invention by providing wireless sensing network systems which can harvest energy from the local environment to provide the power needed for their own operation.

[0054] Numerous sources of ambient energy can be exploited for energy harvesting, including solar, wind, thermoelectric, water/wave/tide, rotation, strain, and vibration. For shipboard monitoring applications below deck and for monitoring tire pressure and temperature, mechanical energy harvesting devices, such as those that harvest strain or vibrational energy are preferred. In Navy applications, strain energy would be available on engine mounts, ship hull sections, and structural support elements. Vibrational energy would be available on diesel turbine engine components, propeller shaft drive elements, and other machinery and equipment. This energy could be harvested using electromagnetic devices (coil with permanent magnet), Weigand effect devices, and piezoelectric transducer (PZT) materials. Of these, the PZT materials hold the most promise.

[0055] Recent developments in single crystal PZT have led to significant improvements in the mechanical-to-electrical conversion coefficients (coupling coefficients), from 60% efficiency to 90% efficiency. Single crystals also exhibit higher operating strain capabilities than conventional PZT materials (0.2% vs. 1.4%). These materials are available through TRS Ceramics (State College, Pa. http://trsceramics.com/Single_Crystal.pdf).

[0056] Furthermore, PZT fibers have recently been made commercially available at low cost for active damping of

sporting equipment, such as baseball bats, tennis rackets, and skis (Advanced Cerametrics, Lambertville, N.J., www.advancedcerametrics.com/piezo_fiber.html). These fibers may be directly bonded to a straining element or structure to generate electrical energy that can be harvested. Major advantages of these fiber piezoelectric materials is that they can tolerate the loss of many individual fibers in a bundle and still function well. Since they are in mass production, they may be obtained readily and at relatively low cost. Because of these advantages the present invention describes the use of these PZT materials for energy harvesting wireless sensor networks. However, other devices and other sources of ambient energy can also be used.

[0057] The present inventors have used single crystal and PZT fibers to create working energy harvesting prototypes that provide sufficient energy to power StrainLink wireless sensor transmitters available from MicroStrain, Inc. (StrainLink, http://www.microstrain.com/slink.html).

[0058] Energy harvesting addressable wireless sensing node **18** can be attached to machine or structure **19** that is subject to vibration, as shown in **FIG. 1***a*. In one embodiment, PZT **20** is mounted to cantilever **22** which can be tuned with variable mass **24**, as shown in **FIGS. 1***b* and **1***c*, to provide a device resonance frequency close to the vibration frequency of machine or structure **19**, thereby optimizing energy harvesting. PZT **20** can be either a crystal or a fiber. Cantilever **22** is mounted on PC board **25** in enclosure **26**.

[0059] Alternatively, a large sheet of PZT fiber **27** can be embedded in material of hull **28** of ship **30** so vibration or strain energy transmitted through hull **28** can be harvested, as shown in **FIG. 2**. Large sheets of PZT fiber **27** are preferred because tuning is not readily available to harvest the strain energy. A structure, such as hull **28** or the deck of a bridge bends only a limited amount, and the bending cannot be tuned as can flexural element by adjusting mass so as to take advantage of resonance frequency to harvest more of the energy.

[0060] In the mechanical vibration embodiment, the source of mechanical energy, such as machine or structure **19**, is converted to electrical energy in energy harvesting addressable wireless sensing node **18'**, which includes a miniature electric generator, such as PZT **20**, as shown in **FIG. 3***a*. A miniature electric generator can also be provided with a coil and magnet in relative rotational motion, as for example, would be available in the vicinity of spinning machinery or wheels.

[0061] Electrical power generated in PZT **20** is rectified in rectifier **40**, stored in electrical storage device **42**, and once sufficient energy has been stored, is provided to a load, such as wireless sensing module **44**, by means of controller **46**.

[0062] In one experiment, a single crystal PZT **20** was connected to the circuit shown in **FIGS. 3***a*, **3***b*, while vibration was applied to PZT **20**. With a DC voltmeter across storage capacitor **42**, upwards of 20 volts was measured across the capacitor with approximately 0.08 inch deflection of the PZT **20** at a 50 Hz rate.

[0063] PZT **20** is inherently a high impedance device which provides a nearly constant current, so the storage capacitor charges linearly with time. Thus, the time for storage capacitor **42** to charge is found from T=CV/I where C=capacitance value, V=voltage charged to, and I=the charging current.

[0064] The Microstrain StrainLink transmitter is also a constant current load, so calculating the discharge uses the same formula. A 47 uF cap charged to 16 volts will supply 2.8 mA for 268 mS discharging to zero volts. A low power StrainLink transmitter can be connected as load **44** in the circuit of **FIG. 3***a*, **3***b* and can run for 224 mS before reaching the reset voltage of 2.63 volts. This is enough time to transmit data from several sensors. Obviously a bigger storage capacitance would supply a longer operating time as would any reduction in load current presented by the transmitter. However, a longer time would be needed to charge a larger capacitor. Furthermore, the practicality of such a system is dependant on the continued availability of vibration input energy. Thus, the present device is ideally suited to applications where ambient vibration is continuous for long periods to provide for the self-discharge rate of storage capacitor **42**, to provide power consumed by the circuit used to monitor charge and switch on the load, as well as to power the load.

[0065] In an alternative embodiment PZT **20** device could be replaced with coil winding **47***a* that is closely coupled to power transmission line **47***b* that would allow energy in the magnetic field around the transmission line to be harvested, as shown in **FIG. 4**. Such a configuration could be used with thermocouples **47***c* to measure the temperature of transmission line **47***b* and detect an overheated condition in transmission line **47***b*. As with the PZT embodiment, the frequency of transmissions is proportional to current in the transmission line **47***b*.

[0066] Wireless sensing module **44** includes microcontroller or microprocessor **48**, which controls provision of power to A/D converter **50**, sensors **52**, non-volatile memory **54**, and RF transmitter **56**, as shown in **FIG. 5**. Sensors can include such sensors as a temperature sensor, a strain gauge, a pressure sensor, a magnetic field sensor, an accelerometer, or a DVRT. By selectively providing power to or withholding power from these devices microcontroller **48** can achieve substantial energy savings. Microcontroller **48** also controls flow of data from A/D converter **50**, from sensors **52**, to and from nonvolatile memory **54** and to RF transmitter **56**. A transceiver can be provided instead of RF transmitter **56** to enable two way communication, all powered by ambient vibrational energy.

[0067] The strain or vibrational energy **57** from the ambient environment is provided to PZT transducer **20** mounted on a machine, structure, or live subject, as shown in block diagram form in **FIG. 3***a* and in schematic form in **FIG. 3***b*. As indicated above, electrical output of PZT **20** is rectified in rectifier **40**. DC output of rectifier **40** charges storage capacitor **42**. Controller **46** monitors charge stored on storage capacitor **42**, and when sufficient, provides Vcc power to wireless sensing module **44** for transmitting sensor data through antenna **68** to receiver **69***a* on base station **69***b* (**FIG. 1***d*). Receiver **69***a* can be a transceiver. Controller **46** includes monitoring device **70**, and switch Q1, which is formed of MOSFET transistor **72**. When voltage across capacitor **42** is sufficient, monitoring device **70** turns on to provide Vcc to wireless sensing module **44**. To reduce leakage and ensure that wireless sensing module **44** remains

fully off and does not load storage capacitor **42** when voltage across storage capacitor **42** is below a threshold, transistor **72** is provided. When transistor **72** turns on, ground connection from wireless sensing module **44** is established.

[**0068**] Transistor **72** is needed because when voltage provided by storage capacitor **42** is too low, monitoring device **46** cannot provide its output in a known state. Monitoring device **46** may turn on falsely and load down storage device **42**, preventing it from ever charging up. Monitoring device **46** is not itself a reliable switch unless supply voltage is above a threshold. To provide for operation in the regime when supply voltage is below that threshold, switch **72** is provided to ensure that wireless sensing module **44** remains fully off. Switch **72** connected between wireless sensing module **44** and ground and has a single threshold.

[**0069**] In operation in one embodiment, monitoring device **70** becomes valid at 1.8 volts. Switch Q1 transistor **72** turns on at 2.0 V, enabling wireless sensing module **44** when storage capacitor **42** has sufficient charge to operate monitoring device **70** properly and can hold it off. Finally, when voltage at storage capacitor **42** reaches 6.3 V monitoring device **70** turns on and transfers charge from storage capacitor **42** to power wireless sensing module **44** for a brief period, until voltage discharges back to 2.9 volts, at which point monitoring device **70** turns off further transfer, and monitoring device **70** therefore continues to be in a valid state for subsequent operation, well above the 1.8 volts level needed for proper operation in a determinate state.

[**0070**] Thus, when sufficient charge is provided to storage capacitor **42** to provide a voltage equal to a higher threshold, monitoring device **70** turns on and connects wireless sensing module **44** to storage device **42**. This discharges storage device **42** down to a lower threshold voltage at which point monitoring device **70** turns off, disconnecting wireless sensing module **44** from storage device **62**. Storage device **42** can then recharge from energy supplied from PZT **20**. However, if storage device **42** fully discharges, or if potential across storage device **42** falls below the lower threshold then monitoring device **70** may not be sufficiently powered to operate correctly. It may not fully disconnect wireless sensing module **44** from storage device **42**, and thus, wireless sensing module **44** may continue to load storage device **42**, preventing it from ever recharging. To prevent this possibility, switch **72** is provided which disconnects wireless sensing module **44** from ground when potential across storage capacitor **42** falls somewhat below the lower threshold.

[**0071**] The present inventors found that impedance mismatch between PZT **20** and storage capacitor **42** limits the amount of power that can be transferred from PZT **20** to storage capacitor **42**. They recognized that energy transfer was limited by the fact that AC power generated by PZT **20** is presented by the PZT at a very high impedance and at low frequency. They observed that PZT **20** behaves as a constant current source, and that when piezoelectric elements are used to charge capacitors, such as storage capacitor **42**, charging is determined by the short circuit current capability of PZT **20**. When storage capacitor **42** is charged from a constant current source, such as PZT **20**, storage capacitor **42** will charge at a rate proportional to the current provided by the constant current source. They further recognized that since the current available from PZT **20** is low, a long time is needed to charge a large capacitance, such as storage capacitor **42**, needed for powering devices such as wireless sensing module **44** or other transmitters. They recognized the further difficulty that the larger leakage current presented by larger capacitors may exceed the charge rate of the constant current provided by PZT **20**.

[**0072**] The present inventors developed a circuit that efficiently converts power from a high impedance current source, such as PZT **20**, to a low impedance voltage source capable of charging a capacitor or battery storage device. The inventors also developed an efficient way to determine when enough power has been accumulated and applying that accumulated power to a useful purpose.

[**0073**] In addition, the present inventors recognized that if the available power in the piezoelectric element were to be efficiently converted from its low current and high impedance current source to a voltage source, the capacitor could be charged much faster than if the same capacitor were charged directly from the short circuit current of the piezoelectric element without this conversion. For example, if a voltage converter can present a 500K load to the piezoelectric element, approximately matching its impedance, the element will deliver 17.5 volts at 35 uA or 610 microwatts. If this power was then converted down to 100 ohms source impedance, even at 80% efficiency, the charge current would be more than 2.2 mA. By comparison, the output at the same level of excitation of the piezoelectric element when loaded to 100 ohms without a converter, is 6 millivolts at 60 uA or 0.36 microwatts, about 1,700 times less power.

[**0074**] The inventors of the present invention conducted empirical tests on a sample of piezoelectric material in order to determine a viable topology of conversion circuit. A test was performed on a sample of highly flexible piezoelectric fiber. The sample was mounted in a 3 point bending jig with a strain gauge attached to the material, and excited to the same strain levels at three different frequencies. A decade resistance substitution box was used to load the output in order to determine the optimum load impedance for maximum power out of the material under these conditions. The same low current was measured as the load resistance was varied from 100 ohms to 50 Kohms as shown in **FIG. 9**. The optimum load impedance, that delivers maximum power, was found to be about 500 Kohms, as shown in **FIG. 10**.

[**0075**] The present inventors found that further substantial improvement in energy harvesting is available by adding an impedance converter circuit to the circuit of **FIG. 3***a* that provide better impedance matching to the high impedance of PZT **20**, while still finally providing the large capacitance needed to power wireless sensing module **44**. The improvement to energy harvesting addressable wireless sensing node **18**", illustrated in block diagram form in **FIG. 11***a* and in a schematic diagram in **FIG. 11***b*, provides an additional stage of charge storage, monitoring, switching, and impedance conversion between rectifier **40** and controller **46** of **FIG. 3***a*. In addition to providing more efficient transfer of energy from PZT to long term storage device **42**', the improvement allows a much larger capacitor or a battery to be used for that long term storage **42**', and this enables more information transfer by wireless sensing module **44**.

[**0076**] PZT **20** connected to a source of mechanical energy, such as vibration or strain **57**, produces a high impedance AC voltage in accordance with the strain or

vibration **57** applied to PZT element **20**. D1 and D2 (**FIG. 11***b*) form Schottky barrier rectifier bridge rectifier **40** that converts the AC voltage from PZT **20** to DC. PZT **20** charges reactance element **78**, such as small capacitor C2 along curve **80** until a voltage equal to Vth**3** is reached, as shown in **FIG. 11***a* and **FIG. 6***a*.

[**0077**] Voltage Vth**3** is sufficient to turn on switch **2**, transistor **82** which connects DC-DC converter **84** to ground, enabling DC-DC converter **84** to turn on and operate. When DC-DC converter **84** turns on, it converts the high voltage stored on small capacitor C2 to a low voltage at a low impedance for providing a small boost **86** to the charge on long term storage capacitor **42'**, capacitor C1, as shown along charging curve **88** in **FIG. 6B**. While long term storage capacitor C1 is charging, small capacitor C2 is discharging. The discharge of small capacitor C2, is shown along curve **90** in **FIG. 6***a*, providing the charge to boost the voltage of long term storage capacitor C1 by the small step **86** shown in **FIG. 6***b*. Voltage scales are the same on **FIGS. 6***a*, **6***b*, **6***c*. Small capacitor C2 continues to discharge through DC-DC converter **84** until voltage on small capacitor C2 equals voltage on long term storage capacitor C1. Thus, as long term storage capacitor C1 charges up, small capacitor C2 discharges less and less fully, as shown by the continuous increase in the discharge voltage level **92** in **FIG. 6A** with each charging and discharging cycle of small capacitor C2, while the charge level of long term storage capacitor C1 continuously increases.

[**0078**] Although voltage on small capacitor C2 discharges, second switch **82** remains on because of delay introduced by capacitor C3 in parallel with resistor R2 in voltage divider **94**. Thus, DC-DC converter **84** remains on while voltage across capacitor C2 drops below Vth**3** as shown in **FIG. 6A**. R4, R5 and second switch **82** form a switch that disables any conversion until enough voltage is present on C2 to convert. This switch threshold is set to approximately 22 volts. DC-DC converter **84** is a high frequency stepdown DC to DC converter that has a typical quiescent current of 12 uA and is capable of 80% efficiency even with small load current. In this embodiment, DC-DC converter **84**, U2 is an LT1934-1 (Linear Technology, Milpitas, Calif.). This converter was chosen due to its very low quiescent current.

[**0079**] As also described for the circuit of **FIGS. 3***a* and **3***b* and the circuit of **FIGS. 11***a* and **11***b*, resistors R1, R2, R3, and comparator U1 form monitoring device **70***a* and also form voltage sensitive switch **70***b* that turns off connection to load **44** until enough charge has been accumulated on storage capacitor **42**, **42'** to run load **44**. Load **44** can be multiple wireless sensing module **44**, or an array of such modules, as shown in **FIG. 11***b*.

[**0080**] Monitoring device **70***a*/voltage sensitive switch **70***b* is in an undefined state, however, until at least **1.8**volts is available on its Vcc pin **7**, which is connected to storage device **42**, **42'**. To avoid problems from this undefined state, MOSFET switch Q1 is provided to disconnect load **44** until voltage on storage device **42**, **42'** has reached 2.0 volts. R2 & R3 set the turn-on threshold V_{th2} of voltage sensitive switch **70***b* to 6.3 volts. R1 provides hysteresis to comparator U1 giving it two thresholds. Voltage sensitive switch **70***b* now turns on when voltage on storage device **42**. **42'** reaches the higher threshold V_{th1} of 6.3 volts and stays on until the voltage on storage device **42** discharges down to V_{th2} the lower threshold of 2.9 volts. When storage device **42**, **42'** reaches its higher threshold of 6.3 volts there is enough charge available on storage device **42**, **42'** to power load **44** to operate for a brief period, for example, to transmit a burst of data. Load **44** may be a StrainLink transmitter or a data logging transceiver.

[**0081**] None of the charge provided to long term storage device **42'**, is supplied to wireless sensing module **44** until the voltage on long term storage device **42'** reaches the higher threshold, V_{th1}, as shown in **FIG. 6B**. When voltage on long term storage device **42'**, C1 reaches V_{th1}, monitoring device **70** now turns on, as described herein above. Switch Q1 (transistor **72**) has already turned on before V_{th2} was reached, and charge is now transferred from long term storage device **42'**, C1 to operate wireless sensing module **44**, as shown in **FIGS. 6B and 6C**. Voltage on long term storage device **42'**, C1 discharges to V_{th2}, about 2.9 volts at which point monitoring device **70** turns off.

[**0082**] If voltage to switch Q1 declines too far, switch Q1 will turn off, and this shuts off transmitter **44** until enough energy is accumulated in storage device **42'** to send another burst of data.

[**0083**] Multiple wireless sensing modules **44** or other devices can be provided on a network, each powered as described herein with energy harvested from its environment. The multiple wireless sensing module **44** can transmit on different frequencies or a randomization timer can be provided to add a random amount of time after wake up to reduce probability of collisions during transmission. However, since the time for charging is likely to differ from one wireless sensing module **44** to another, a randomization timer may not be needed. Each wireless sensing module **44** will transmit an address as well as data. Transceivers can be provided to each wireless sensing module **44** to provide two way communication. Preferably, if a battery is used that is recharged from the environment, sufficient energy will be available so it can wake up periodically to determine if something is being transmitted to it. If not it can go back to sleep mode. If so, it can receive the transmission. All the members can be managed by a broadcast signal or each wireless sensing module **44** can be addressed and programmed individually.

[**0084**] The present inventors have applied the energy harvesting system to design a device for embedding in a tire by a tire manufacturer for harvesting energy and for monitoring parameters, such as tire temperature and pressure on a vehicle and for transmitting the data, as shown in **FIG. 7**. The cross section of tire **100** shows the placement of PZT **102**, or several such PZT elements, on or within interior sidewall **104** of tire **100** for gathering strain energy from flexing of tire **100** on rim **101** as the tire rotates. PZT **102** is connected to provide power to energy harvesting addressable wireless sensing node **106** for transmitting data from temperature and pressure sensors **108**, such as SensorNor from Horten, Norway, to report this tire data. Energy harvesting addressable wireless sensing node **106** can be programmed to provide it with a 128 bit address. With such a large address there are enough combinations possible to allow every tire in the world to have a unique address. Thus, receiver **110** mounted in the vehicle can receive a signal indicating tire sensor data for each of the tires on the vehicle,

as shown in **FIG. 8**. A display can provide the information to the operator. Alternatively, an alarm can signal when tire pressure or temperature is outside specified limits. Interference from other vehicles can be avoided by displaying only data from tires having known addresses.

[**0085**] Local antennas **112** can be provided in each wheel well (not shown) and the power output of energy harvesting addressable wireless sensing node **106** can be adjusted to provide reliable communications within the wheel well of the vehicle while avoiding interference with transmitters on adjacent vehicles.

[**0086**] Receiver **110**, having antennas **112** positioned in each wheel well of the vehicle, can rapidly scan antennas **112** to determine the address and position of each tire on the vehicle. Because of the scanning of the antennas, even if tires are rotated, the display can indicate the location of a tire having a problem. Most modern receivers have the capability of accurately measuring received signal strength with fairly high resolution. In the case of inner and outer wheels in a single wheel well, these received signals can be qualified by received signal strength indication to distinguish the tires in the wheel well, even if they are rotated. Thus, the tire further from the antenna will have the weaker signal strength. In addition, the serial numbers of each tire would also be logged in the receiver flash memory to distinguish tires on the vehicle for feedback to a tire manufacturer.

[**0087**] One alternative to the tire position problem that does not require scanning or multiple antennas, is to have a technician sequentially scan a bar code on the tires at the time of tire installation on the vehicle, and communicate the tire position information to the automotive communications (CAN) bus or other communications bus within the vehicle, or even directly to the receiver. The position information is provided using a different protocol than the information tires are sending so this information can remain stored in the receiver while other data about the tire changes with each reading. In this way one receive antenna could receive data and an identification code from all tires on the vehicle, and the stored table linking identification and tire position can be used to communicate the position, temperature, and pressure of each tire. Interference from transmitters on adjacent vehicles is avoided since they would not have known identification codes.

[**0088**] The present inventors have also found ways to reduce power consumption as well as to provide power from energy harvesting. They recognized that power consumed by all of the system's components (sensor, conditioner, processor, data storage, and data transmission) must be compatible with the amount of energy harvested. Minimizing the power required to collect and transmit data correspondingly reduces the demand on the power source. Therefore, the present inventors recognized, minimizing power consumption is as important a goal as maximizing power generation.

[**0089**] The present inventors have developed and marketed sensors that require very little power. For example, they have previously reported on micro-miniature differential variable reluctance transducers (DVRT's) capable of completely passive (i.e., no power) peak strain detection. These sensors can be embedded in a material and will continuously monitor for the existence of a damaging strain state. By providing a hermetic seal the sensors can withstand harsh environmental conditions (moisture, salt, and vibration). The sensors can be reset remotely using shape memory alloys and (remotely applied) magnetic field energy, as described in a copending patent application Ser. No. 09/757,909, docket number 1024-035, incorporated herein by reference. The present inventors have also recently developed totally passive strain accumulation sensors, which can be used to monitor fatigue. Furthermore, they have demonstrated novel radio frequency identification (RFID) circuits with the capability of interrogating these sensors in under 50 microseconds using less than 5 microamperes of current. Thus, although small amounts of energy may be available from energy harvesting, the energy so collected is enough to power sensors, electronics, and transmitters.

[**0090**] The present inventors have also developed wireless web enabled sensor network (WWSN) systems that require very little power. One strategy for minimizing power is demonstrated by the WWSN network architecture illustrated in **FIG. 12**. This is an ad hoc network that allows thousands of multichannel, microprocessor controlled, uniquely addressed sensing nodes TX to communicate to a central, Ethernet enabled receiver RX with extensible markup language (XML) data output format (http://www.microstrain-.com/WWSN.html). A time division multiple access (TDMA) technique is used to control communications. TDMA allows saving power because the nodes can be in sleep mode most of the time. Individual nodes wake up at intervals determined by a randomization timer, and transmit bursts of data. By conserving power in this manner, a single lithium ion AA battery can be employed to report temperature from five thermocouples every **30** minutes for a period of five years. The XML data format has the advantage of allowing any user on the local area network (LAN) to view data using a standard Internet browser, such as Netscape or Internet Explorer. Furthermore, a standard 802.11b wireless local area network (WLAN) may be employed at the receiver(s) end in order to boost range and to provide bi-directional communications and digital data bridging from multiple local sensing networks that may be distributed over a relatively large area (miles). Further information about a wireless sensor network system developed by the present inventors is in patent application docket number 115-004, incorporated herein by reference.

[**0091**] Another strategy for creating low power wireless sensor networks is demonstrated by MicroStrain's Data Logging Transceiver network (http://www.microstrain.com/DataLoggingTransceiver.html) as described in copending U.S. patent application Ser. No. 09/731,066, docket number 1024-034, incorporated herein by reference. This system employs addressable sensing nodes which incorporate data logging capabilities, and a bidirectional RF transceiver communications links. A central host orchestrates sample triggering and high speed logging to each node or to all nodes. Data may be processed locally (such as frequency analysis) then uploaded when polled from the central host. By providing each sensor node with a 16 bit address, as many as 65,000 multichannel nodes may be hosted by a single computer. Since each node only transmits data when specifically requested, the power usage can be carefully managed by the central host.

[**0092**] For further energy savings, only limited data collected by sensors may be transmitted. For example, minimum, maximum and average data can be transmitted to reduce the amount of data transmitted and to thereby save

energy. Standard deviation can also be locally calculated and transmitted, saving transmission time and energy.

[0093] For sensors detecting information where a band of frequencies is measured, such as measurements of a vibrating source with an accelerometer, a fast Fourier transform can be locally calculated and only the frequencies of vibration and the magnitude of vibration need be transmitted, rather than the entire waveform, to reduce the amount of information transmitted and to save energy.

[0094] The present inventors provided improved designs of each element of the entire measurement system, including the: vibrating/straining structure, piezo harvesting circuit, sensing circuit, microprocessor, on board memory, sensors, and RF data transmitter/transceiver to provide a system that operated with low power. The present inventors then built a prototype that both improved on the performance of energy harvesting devices and that reduced the energy consumption of each element of the measurement system, including the vibrating/straining structure, piezo harvesting circuit, sensing circuit, microprocessor, on board memory, sensors, and RF data transmitter/transceiver, as shown in **FIGS. 3***a*, **3***b*, **4** and **5**.

[0095] A demonstration energy harvesting circuit was built using a PZT fiber as its input, as shown in **FIGS. 3***a*, **3***b*. The PZT device generates a voltage that is rectified by low forward drop diodes. This rectified voltage is used to charge a storage capacitor. The transfer is purely a function of the short circuit current of the piezoelectric structure, minus the loss of the rectifier stage, the self discharge of the storage capacitor, and any leakage current in the switch in its 'off' state. The behavior of this configuration is similar to charging a capacitor from a constant current source. The time required to charge the capacitor is inversely proportional to the amplitude of the strain or vibration applied to the PZT element at a given frequency of strain, and also proportional to the frequency of strain at a given amplitude. Once the voltage sensing switch detects that enough charge is stored on the capacitor, the load is connected to the storage capacitor. The load in this demonstration circuit is a MicroStrain Strainlink RF sensor microtransmitter. (MicroStrain, Inc. Williston, Vt. http://www.microstrain.com/slink.html) StrainLink is a multichannel, digital wireless transmitter system which allows direct sensor inputs from five pseudo differential (single ended) or three true differential channels. StrainLink features on-board memory, with user programmable digital filter, gain, and sample rates and with built-in error checking of pulse code modulated (PCM) data. Once programmed, these settings reside in the transmitter's nonvolatile memory, which will retain data even if power is removed. The StrainLink transmitter is compatible with numerous sensor types including thermocouples, strain gauges, pressure sensors, magnetic field sensors and many others. The transmitter can transmit frequency shift keyed (FSK) digital sensor data w/checksum bytes as far as ⅓ mile on just 13 mA of transmit power supply current. During testing, the transmitter operated for approximately 250 mS on the power stored in the charged capacitor. This was ample time for the StrainLink to acquire data from a sensor and transmit multiple redundant data packets containing the sensed data.

[0096] Voltage sensing switch **70***b* was implemented using a nano-power comparator with a large amount of hysteresis. Some design difficulties arise when using an electronic device to perform such switching tasks. Voltage sensitive switch **70***b* itself needs to be powered from the source it is monitoring. When the available voltage is near zero the state of switch **70***b* is indeterminate. This can present a problem when the circuit is initially attempting to charge the capacitor from a completely discharged state. In the demonstration circuit as built, the switch defaults to 'on' until the supply voltage to its Vcc exceeds 0.7V, then it will turn off until the intended turn-on voltage level is reached. The transmitter draws constant current, except when the supply voltage is below the transmitter's regulator threshold. In this condition the current increases slightly from the normal operating current of 11 mA to about 15 mA at less than 1 volt. Because of this, and the fact that the switch is 'on' below approximately 0.7 volts, a silicon diode with equal to or greater than 0.7 V forward drop was added from the output of the switch to the transmitter power pin. This allows the storage capacitor voltage to charge to the point where the switch is active before the transmitter starts drawing current. The settings for voltage trip points were adjusted to 6.3V 'on' and 2.9V 'off'.

[0097] In practice, the voltage sensing switch is still falsely 'on' at supply voltages of up to 1 volt, at which point the diode is already conducting power into the load. Drawing current from the storage capacitor at this low voltage slows the charging of the capacitor.

[0098] This creates a problematic "turn-on" zone where the capacitor is being drained at the same time it is being charged. This makes it difficult for the system to initially charge itself enough to begin operating properly. If enough strain energy is applied to the PZT element during initial system startup, then this turn-on zone is exceeded, and the system works properly.

[0099] The present inventors recognized that switching the positive rail e.g. a "high-side switch," inherently requires some supply voltage to be present in order to properly turn the load "off." This is not the case with a "low-side switch," or one in which the minus lead is switched to DC ground. **FIGS. 3***a*, **3***b*, **11***a*, **11***b* illustrate an improvement to the switch that will eliminate the turn-on zone problem. It employs both the existing high side switch implemented with nanopower comparator **V1**, LTC **150**, and the addition of a low side switch in the DC return path of the power source. The low side switch is implemented with an N channel enhancement mode MOSFET, such as first switch **Q1**, **72** that has a gate turn-on threshold higher than the minimum operating voltage of the high side switch. This combination eliminates the disadvantages of the high side switch and the difficulties with implementing the appropriate switching function using only low side switch components.

[0100] High side voltage sensing switch **V1** may falsely turn on when storage capacitor **42'** is charged to between 0.7 and 1.0 volts. No current will flow, however, until the supply voltage exceeds the Vgs voltage of the gate of MOSFET **Q1**, **72**. The Vgs voltage is typically greater than 1.5 volts even with so-called logic level MOSFETS that are optimized for full saturation at logic level (5 volt) gate to source voltage. Once the charge on capacitor **42'** has exceeded Vgs, the MOSFET will allow current to pass, but by that point, the voltage sensing circuit will have sufficient supply power to function properly. These changes allow energy harvesting circuit **18'**, **18"** to efficiently begin charging itself even when it starts from a completely discharged state.

[0101] Efficiency of the energy storage element is an important factor in implementing efficient designs because the energy may need to be stored for significant time periods before it is used. In the demonstration energy harvesting system, an aluminum electrolytic capacitor was utilized as the storage element. This is not an ideal choice since its leakage loss is relatively high. In fact, it can be as much as ten times higher than that of the voltage sensing switch used to monitor the capacitor voltage. To minimize this problem, alternative capacitor technologies, such as tantalum electrolytic and ceramic, can be used.

[0102] No matter what capacitor technology is used, charge leakage is likely to be a limiting factor in applications where long term storage of charge is necessary. Batteries, can be used for long term energy storage device **42**, **42'**, and have advantage of essentially zero charge leakage (<1% energy loss per year). Thin film batteries, such as those provided by Infinite Power Solutions, Littleton, Colo. www.infinitepowersolutions.com, offer advantage of being able to be charged and discharged in excess of 100,000 times. In addition, battery chemistry allows for a battery cell to be continuously charged when power is available, as supplied by the PZT. The battery cells have high enough peak energy delivery capability (10 mA pulsed power) to allow for short bursts of RF communications.

[0103] Reduced power consumption is inherently beneficial to the performance of systems using harvested energy. A significant reduction in power consumption can be realized through the use of embedded software in microcontroller **48** that controls the power consumed by the sensors, signal conditioning, processing, and transmission components of the energy harvesting wireless sensing systems (**FIG. 5**). By adjusting the time these devices are on, for example, power consumed can be reduced. In addition embedded processor **48** can be programmed to process and store sensed information rather than immediately transmit, and thereby reduce the frequency of data transmission. Finally the power levels used for RF communications can be reduced by bringing a receiver closer to the sensor nodes. This can be accomplished by providing multiple receivers for a sensor network, by bring an operator with a receiver closer, or by providing a mobile robot that approaches sensors and reads their data, as more fully described in copending application docket number 115-004, incorporated herein by reference.

[0104] The most direct strategy to reduce the power consumed by the sensors and signal conditioners is to use sensors that do not require power, such as thermocouples, piezoelectric strain gauges, and piezoelectric accelerometers. For thermocouples, cold junction compensation can be provided with a micropower solid state temperature sensor (National Semiconductor, Milpitas, Calif.) that typically consumes 20 microamps current at 3 volts DC, for a continuous power consumption of only 0.06 milliwatts.

[0105] A second strategy is to employ sensors that do not need to transmit data frequently, such as temperature and humidity sensors. There are several very low power humidity sensors, for example from Honeywell that can be employed along with thermocouples or solid state temperature sensors to provide periodic data updates. For these types of measurements, the reading changes slowly, so energy can be conserved by transmitting the data infrequently.

[0106] A third strategy to minimize the power consumed by sensors **52** is to pulse the power to sensors **52** and to time the reading of data from A/D converter **50** appropriately.

[0107] With the sensor on only for a brief period of time to achieve a stable reading and to obtain that reading for storage or transmission, much energy can be saved. Microstrain has successfully used this technique for powering and gathering data from strain gauges used in medical implants. The current, and therefore the power, savings that can be realized are significant. For example, a 350 ohm strain gauge bridge excited with 3 volts DC will consume approximately 8.6 milliamps. If powered continually, this represents a power drain of 25 milliwatts. By only providing the excitation voltage at periodic intervals and performing digital data conversion under microprocessor control, we have been able to reduce the sensor excitation time to 200 microseconds. For applications where a strain gauge reading is required every 100 milliseconds (10 Hz), the effective power drain is reduced by a factor of 500, (from 25 to only 0.05 milliwatts).

[0108] Power reductions in the signal conditioning are also realized by using highly integrated circuits (IC), such as the AD7714 by Analog Devices (Norwood, Mass.), that use very low power and combine a programmable gain instrumentation amplifier (110 dB CMRR), multiplexer, and 22 bit sigma-delta analog to digital converter. The current consumed by the AD7714 is 200 microamps at 3 volts DC, or 0.6 milliwatts. The AD7714 can be programmed to accept 3 full differential or five single ended sensor inputs. We have successfully employed this IC for use with foil and piezoresistive strain gauges, thermocouples, temperature sensors, torque sensors, and load cells. With a rectifier, a differential amplifier and periodic excitation we have successfully used these ICs with inductive displacement sensors.

[0109] The power consumed by the embedded processor can be reduced by using low power embedded microcontrollers, such as the PIC **16** series from MicroChip Technologies (Chandler, Ariz.). Such embedded processors include integrated instrumentation amplifiers to facilitate sensor conditioning, and integrated radio frequency (RF) oscillators to facilitate wireless communications. By including more capability on the processor, component count and system complexity are reduced, and there is a reduction in power consumed. Further reductions in power consumption are realized by placing the processor in "sleep mode" while the energy harvesting circuit is storing energy in its capacitor bank or battery. The processor (and its integrated amplifier/RF stage) does not come out of sleep mode until the energy harvesting circuit detects that the stored charge is adequate for the programmed task, such as reading a sensor. This prevents the measurement system and processor from loading the energy harvesting circuit and allows storage of energy to proceed most efficiently.

[0110] Further reductions in power consumption may be realized by using lower clock rates for the embedded processor. For example our existing Strainlink digital wireless sensor transmitter product (http://www.microstrain.com/slink.html) is normally run at a clock rate of 4 MHz, and it consumes 600 microamps at 3 volts DC (1.8 milliwatts). For temperature measurement applications (or any other application requiring relatively infrequent data samples), we can reduce the processor's clock rate to 100 KHz, allowing a

more than 20 fold power reduction to 28 microamps at 3 volts DC (0.084 milliwatts). For many health monitoring applications, we can improve performance by simply slowing down the system clock.

[0111] The energy required to power sensors, acquire data, and process/store these data is much lower than the energy required to wirelessly transmit these data. In the preceding discussion, we have shown that thermocouples (0 milliwatts) with cold junction compensation (0.06 milliwatts) could be combined with a smart microcontroller (0.084 milliwatts) and a very low power, highly integrated signal conditioner (0.6 milliwatts) to provide continuous thermocouple readings with a power drain of 0.744 milliwatts. This is in sharp contrast to the RF communications section of the electronics, which may require over 10 milliamps at 3 volts DC for a power drain of 30 milliwatts in order to provide adequate wireless range and good margin in electrically noisy environments.

[0112] By programming the processor to acquire and log sensed data and to compare these data to programmable threshold levels the frequency of RF transmission can be reduced to save power. If the sensed data exceeds or falls below the acceptable operating temperature ranges, then the processor transmits its data, along with its address byte. A **5** randomization timer is be used to insure that if multiple transmitters are transmitting their data (or alarm status) simultaneously, the probability of RF collisions is statistically small, as described in http://www.microstrain.coml/WWSN.html, a paper entitled SPIE Scalable Wireless Web Sensor Networks, SPIE Smart Structures and Materials, March, 2002, by Townsend et al. In the event that threshold levels are not crossed, stored summary data, such as mean, maximum, minimum, and standard deviation, are periodically transmitted over time intervals, such as hourly or daily. Transmission of processed data, such as these trends, and periodic transmission of this data saves more energy.

[0113] The processors may also be programmed to acquire bursts of data from a vibrating structure using an accelerometer. These data may be processed using average fast fourier transform (FFT) and power spectral density (PSD) analyses. The processed data would allow the RF link to transmit only the fumdamental vibration frequencies, which would greatly reduce the amount of data that is transmitted and thereby greatly reduce the "on-time of the RF link.

[0114] To further reduce power consumed by the energy harvesting sensing nodes, we could reduce the RF communications power levels at the expense of range. For some applications, it may be possible for Navy maintenance personnel to approach an area where shipboard monitoring nodes have been placed. The energy harvesting monitoring nodes may also include RF transceivers, which would provide for bidirectional communications. Instead of only periodically transmitting sensed data, these nodes are programmed to periodically activate their integral receiver to detect the presence of maintenance personnel over the wireless link. A handheld transceiver carried by maintenance workers would query various nodes on the network and collect their data into the handheld device. This would greatly reduce the need for long range wireless data communications, and therefore would allow for reduced RF power levels at the remote energy harvesting sensor nodes. Microstrain has developed a high speed data logging transceiver product that could be adapted to this purpose (http://www.microstrain.com/DataLoggingTransceiver.html).

[0115] The vibrational energy harvesting unit is illustrated schematically in **FIG. 1***a*-**1***d*. It consists of circuit board **25** that is rigidly fixed to some vibrating component, such as vibrating machine **19**. Leaf spring **22** is mounted to this base in a cantilever configuration. Proof mass **24** is suspended at the free end of the leaf spring, and this can be adjusted to more nearly provide a resonance frequency close the vibration frequency. One or more PZT elements **20** are bonded to the surfaces of leaf-spring **22** such that when spring **22** deflects, PZT **20** will undergo tensile/compressive strains and therefore be stimulated to generate an electrical output suitable for input into energy harvesting circuit **18'**, **18"**. To maximize the output of PZT **20**, leaf spring **22** is preferably constructed using a "constant strain" profile, as shown in **FIG. 1***c*, such that the strains experienced by the PZT elements are uniform along their length. To provide a constant strain profile, leaf spring flexure element **22** can have a taper, as shown in **FIG. 1***c*. Enclosure **26** surrounds the device to keep contaminants out, and to make the device convenient to handle and damage resistant.

[0116] Enclosure **26** measures approximately 50×50×150 mm and leaf spring flexure element **22** has adjustable proof mass **24** of between 100 and 500 grams. Tuning the unit will be accomplished by adjusting the size of proof mass **24**, which can be washers, as shown in **FIG. 1***c*. The energy harvester is capable of generating sufficient energy to intermittently power a transmitter and several low power sensors, as shown in **FIGS. 3***a*, **3***b*, **11***a*, **11***b*.

[0117] While several embodiments of the invention, together with modifications thereof, have been described in detail herein and illustrated in the accompanying drawings, it will be evident that various further modifications are possible without departing from the scope of the invention. Nothing in the above specification is intended to limit the invention more narrowly than the appended claims. The examples given are intended only to be illustrative rather than exclusive.

What is claimed is:

1.-**76**. (canceled)

77. An electronic system, comprising:

a rotating part;

an energy harvesting circuit mounted on said rotating part, said energy harvesting circuit for harvesting mechanical energy from motion of said rotating part and converting said mechanical energy into electricity; and

a radio frequency communications device mounted on said rotating part and connected to receive electricity derived from said energy harvesting circuit for powering said radio frequency communications device.

78. A system as recited in claim 77, wherein said radio frequency communications device comprises a transmitter.

79. A system as recited in claim 77, further comprising a sensor, wherein data derived from said sensor is transmitted from said rotating part with said transmitter.

80. A system as recited in claim 77, wherein said mechanical energy comprises rotational energy of said rotating part.

81. A system as recited in claim 77, wherein said rotating part has a measurable parameter, said rotating part further comprising a sensor for measuring said parameter of said

rotating part, wherein said radio frequency communications device is for at least one from the group including transmitting said measurement and transmitting data derived from said measurement.

82. A system as recited in claim 81, wherein said energy harvesting device is capable of harvesting energy from rotation of said rotating part.

83. A system as recited in claim 81, wherein said circuit further comprises a rechargeable source of power configured to receive and store energy harvested by said energy harvesting device.

84. A system as recited in claim 83, wherein said rechargeable source of power comprises at least one from the group including a battery and a capacitor.

85. A system as recited in claim 83, further comprising a controller wherein said controller is connected to said rechargeable source of power for monitoring the amount of electrical energy stored in said rechargeable source of power and for switchably connecting said rechargeable source of power to power the transmitter when said stored energy exceeds a first threshold.

86. A system as recited in claim 85, wherein said controller is powered by energy stored in said rechargeable source of power.

87. A system as recited in claim 85, wherein said controller is further for switchably disconnecting said rechargeable source of power from said transmitter when said stored energy is below a second threshold.

88. A system as recited in claim 81, wherein said sensor comprises at least one from the group including a temperature sensor, a strain sensor, and a sensor to measure rate of rotation.

89. A system as recited in claim 81, wherein said circuit further comprises a receiver.

90. A system as recited in claim 89, wherein said circuit comprises a transceiver.

91. A system as recited in claim 81, further comprising a processor for receiving data from said sensor.

92. A system as recited in claim 91, further comprising an A/D converter for converting sensor data to digital data.

93. A system as recited in claim 92, further comprising memory for storing said digital sensor data.

94. A system as recited in claim 93, wherein said memory is at least one from the group including integral with and connected to said processor.

95. A system as recited in claim 93, wherein said memory is connected to receive and store said digital sensor data.

96. A system as recited in claim 93, wherein said memory contains a unique address.

97. A system as recited in claim 91, wherein said processor contains a program to process said data before transmitting.

98. A system as recited in claim 91, wherein said processor controls operation of said transmitter.

99. A system as recited in claim 81, wherein said circuit further comprises a feedback mechanism to adjust operation of said rotating part based on said measurement.

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