Valve health monitoring system utilizing smart instrumentation

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ABSTRACT

The valve monitoring system is a stand alone unit with network capabilities for integration into a higher level health management system. The system is designed for aiding in failure predictions of high-geared ball valves and linearly actuated valves. It performs data tracking and archiving for identifying degraded performance. The data collection types are: cryogenic cycles, total cycles, inlet temperature, outlet temperature, body temperature, torsional strain, linear bonnet strain, preload position, total travel, and total directional changes. Events are recorded and time stamped in accordance with the IRIG B True Time. The monitoring system is designed for use in a Class 1 Division II explosive environment. The basic configuration consists of several instrumentation sensor units and a base station. The sensor units are self contained microprocessor controlled and remotely mountable in three by three by two inches. Each unit is potted in a fire retardant substance without any cavities and limited to low operating power for maintaining safe operation in a hydrogen environment. The units are temperature monitored to safeguard against operation outside temperature limitations. Each contains 902-928 MHz band digital transmitters which meet Federal Communication Commissions requirements and are limited to a 35 foot transmission radius for preserving data security. The base-station controller correlates related data from the sensor units and generates data event logs on a compact flash memory module for database uploading. The entries are also broadcast over an Ethernet network. Nitrogen purged National Electrical Manufactures Association (NEMA) Class 4 Enclosures are used to house the base-station.

Keyword: Health monitoring, valve monitoring, data tracking, data logger, instrumentation, sensors, wireless, hydrogen environment

1. INTRODUCTION

Previous propulsion testing has incurred unexpected schedule delays and costs due to untimely maintenance, repair or replacement of facility valves. The serviceable conditions of valves utilized in the Propulsion Test Facility are critical. These significant pieces of test equipment must be closely monitored and maintained in safe working order. The existing operational data available on the facilities' test critical valves make their life expectation unpredictable. Life and failure predictions can be greatly improved through added valve instrumentation. Conventional instrumentation methods have been cost prohibitive and incapable of being mounted in the desired locations. Applying new integrated electronic technology in the form of smart sensors organized in a data tracking system is an effective way of overcoming these limitations and providing a method of implementing a valve health monitoring system.

It is cost prohibitive to obtain spares for existing valves that have replacement periods of over one year and repair times of approximately six months. It is becoming a necessity to track the life of linearly-actuated valves and high-geared ball valves to efficiently perform testing. Employing a valve monitoring system would aid in managing valve maintenance and failures.

2. METHODOLOGY

A knowledge base on valve operational characteristics would provide insight into life duration and failure predictions. The data tracking and archiving which would be most beneficial in building a knowledge base were identified as:

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cryogenic valve cycles, inlet temperature, outlet temperature, valve body temperature, total valve cycles, cryogenic valve cycles, torsional strain, linear bonnet strain, valve preload position. Monitoring systems on the market were unable to meet all the necessary attributes for implementation in our facilities propulsion test environment. A valve monitoring system was designed to record events associated with the previously mentioned instrumentation collection types. The IRIG B True Time convention was adopted as the required data synchronization protocol since it is used throughout many propulsion test facilities. Therefore, the data events are time stamped in accordance with the facility IRIG B True Time to allow data synchronization within 1 millisecond. The data is then organized into a text file which can be uploaded into the pre-existing facility database.

3. TECHNICAL DESCRIPTION

3.1 The monitoring system fundamental configuration

The valve monitoring system's fundamental configuration consists of a single base station and multiple sensor units. Each sensor unit is assembled for a particular monitoring function. The units were designed for torsional strain, linear strain, temperature, valves cycles and valve position monitoring. These were identified to provide data on the necessary valve attributes that would indicate valve failures and degraded performance. All the sensor units are functionally encapsulated and the detected events are coordinated through the base station. The base station is organized into the main base station controller, flash memory interface, external communication module, bus interface, and several receiver modules. Each receiver unit has a unique address and it is matched up with a remote sensor unit's transmitter. The sensor units are organized into a sensor controller, power regulator, two battery packs, transmitter module, wake-up module, and several instrumentation modules. The configuration is shown in Figure 1.
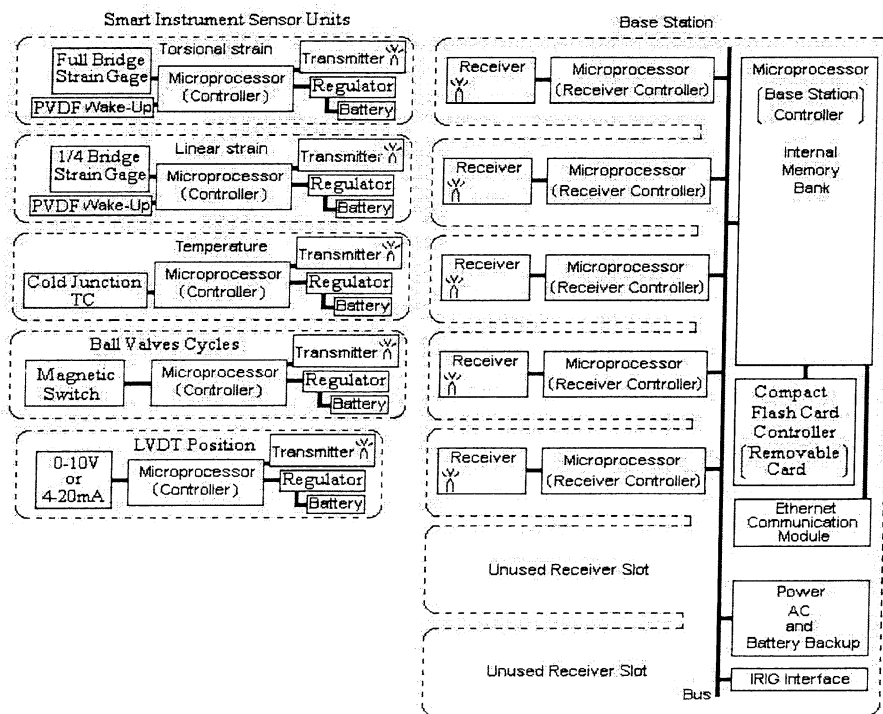

Figure 1: Sensor units' organizational configuration.

The high-geared ball valves and the linearly actuated valves were targeted for health monitoring with this system. The system may be configured for other monitoring duties and not limited to these valve types. The placement and utilization of the sensors are critical for the system's monitoring capabilities.

A method for determining how much a ball valve has been utilized is accomplished by tracking the total number of valve cycles. The number of valve cycles correlated with valve failures provides a basis for making valve life predictions. Another consideration in predicted valve life duration is the number of cycles under cryogenic service. The service duration for valves at cryogenic temperatures will be different from ambient operation. The determination of cryogenic or ambient operation will be made by correlating the inlet and outlet temperatures with each valve cycle. The monitoring system was constructed with a torsional strain sensor unit. The unit was made small enough to be mounted on the ball valve shaft. The clearance necessary for this mounting location is approximately 2 by 3 by 3 inches. The motion of the shaft forces the sensor unit to use a wireless interface. The monitoring system is designed for use in a Class 1 Division II hydrogen environment per National Electrical Code Article 501[1]. All the units are potted in a hydrogen compatible material. The potting material used is blue-epoxy flame retardant 832FRB from M.G. Chemicals[2]. A sensor unit was designed for counting the cycles the ball valve has undergone while in service. The switch sensor unit uses five magnetic position switches for indicating the ball valve state. A Temperature sensor unit was constructed to monitor the inlet and outlet temperatures utilizing cold junction referenced thermocouples (TC). A total of four sensor units are adequate for monitoring a single high-geared ball valve. The typical sensor unit mounting locations on high-geared ball valves are shown in Figure 2.
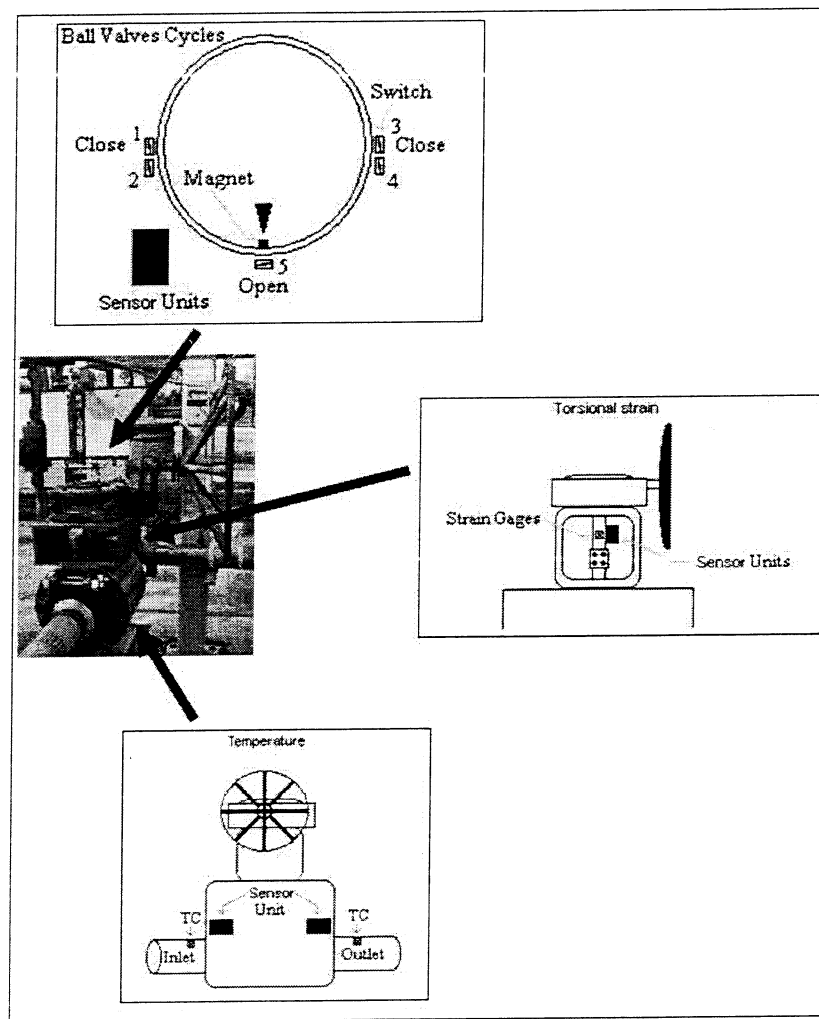

Figure 2: Typical placement of sensor units on high-geared ball valves.

The monitoring system was also designed to observe linearly-actuated valves. The valve plug seating was targeted as a significant point of failure along with packing and seal breakdown. Irregularities in the force during valve cycling can

be determined by logging the strains on each side of the valve bonnet. A linear strain sensor unit was developed for monitoring the axial strain for that application. Observing irregularities in this force will indicate issues involving the linear valve stroke, which will help denote signs of failure in the valve packing or seals. Another sensor unit was designed for tracking the total distance of valve travel and number of directional changes over its duration of service. A signal sensor unit was designed to unobtrusively interface with the Linear Variable Displacement Transducer (LVDT) signal from the internal servo controller. The LVDT signal provides a highly accurate valve position within 0.01% of the valve stroke. The inlet and outlet temperatures are monitored with a temperature sensor unit identical to the one used to monitor temperatures on the high geared ball valve. The temperature sensor unit can also be used to monitor the valve body temperatures. The typical sensor unit mounting locations on linearly-actuated valves are shown in Figure 3.
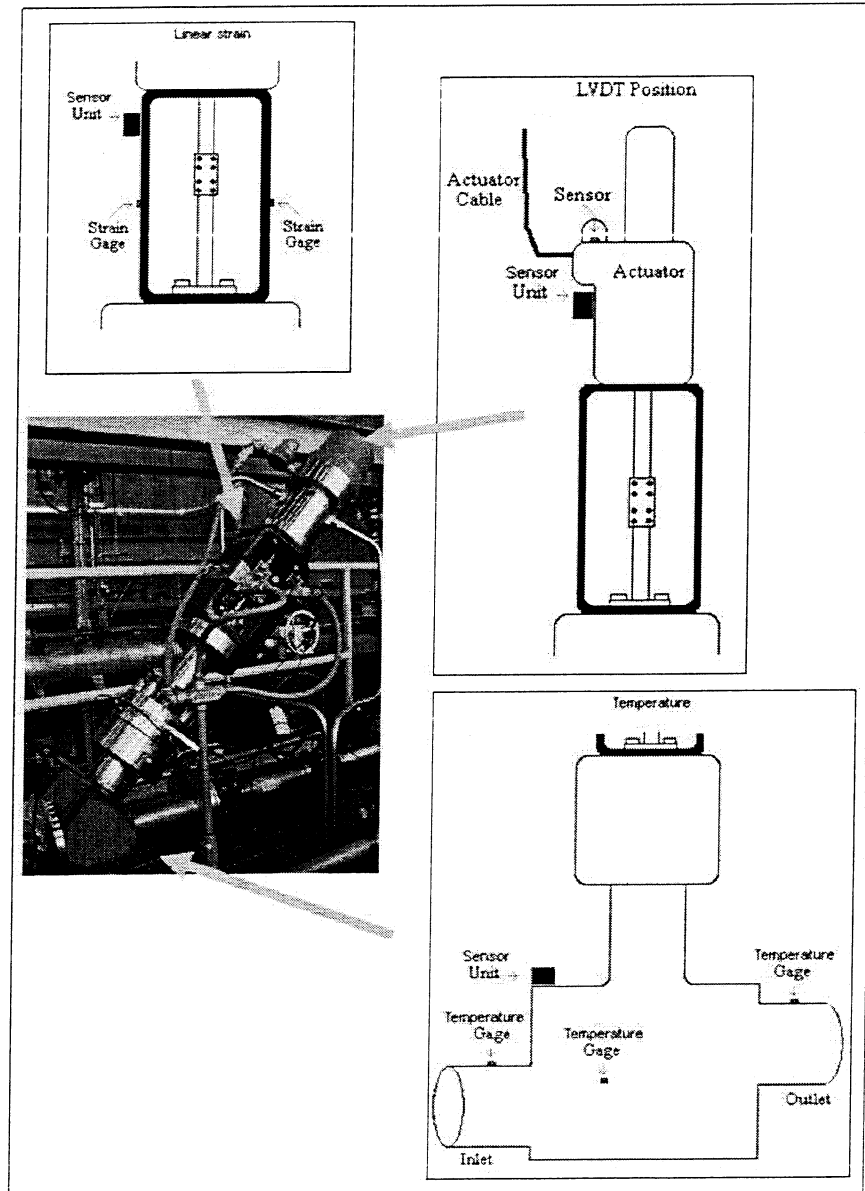

Figure 3: Typical placement of sensor units on linearly-actuated ball valves.

3.1 The monitoring system base

The foundations of the units are microprocessor controller circuits which utilizes the PIC16F887A microprocessor[3] from Microchip Technology Incorporated. This circuit was designed for a dual use function as either the receiver module within the base station or the sensor unit microprocessor controller. The function is determined by the way the integrated circuit board is populated. It contains an oscillator for a 4 megahertz processor speed and another 32.768 kilohertz oscillator for a precision clock. It has a human interface switch and a light emitting diode indicator for performing setup processes and checking battery life. An embedded magnetic reed switch is utilized to eliminate any arcing from switch contact closure. It also has a reboot switch when used as a receiver module.

The TMP36GS temperature component is positioned near the microprocessor for safeguard against operation outside the processor's temperature limitations. It reads the operational temperature within one degree Celsius. It is also positioned directly beneath the battery packs to avoid heating the battery packs beyond the hydrogen explosive limits. The battery packs are not utilized in the receiver module configuration, but the operational temperatures are still monitored for the processor. This internal temperature monitoring component is put into shutdown mode when the sensor unit is in sleep mode to help conserve battery life.

The Linx HP3 transmitter model TXM-900-HP3-PPS[4] is employed in this circuit when configured as the sensor unit. The Linx HP3 receiver model REX-900-HP3-PPS[4] is employed when configured as the receiver module. These provide low-power 902-928 MHz band digital transmissions which meet Federal Communication Commissions requirements. The transmission power is set to limit transmissions to a 35 foot radius for preserving data security. Each receiver/transmitter pair is set to a unique address. The addressing scheme implemented provides eight unique addresses. This restricts each monitoring system to eight sensor units. This is ample for monitoring a single valve, but provisions for enabling over two hundred unique addresses are in place for future implementation.

The microprocessor controller circuit also contains several connections for interfacing to the other sensor unit circuitry. In addition to this, an onboard programming and serial communication interface port header and a communication bus interface header are enclosed within this circuit. The base station's Bus allows a varying number of receiver units to be connected. Each receiver unit has a unique address and it is matched up with a remote sensor unit.
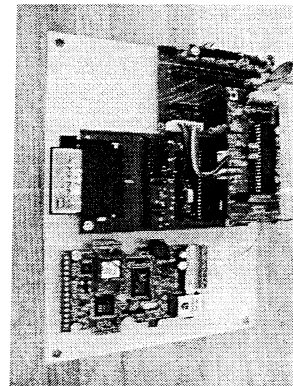

Figure 4: The base and enclosure

Figure 5: The base station

3.2 The monitoring system sensor units

The microprocessor, regulator, transmitter and internal temperature circuitry are common to all the sensor units. The piezoelectronic wake-up circuitry is only necessary in the strain sensor units. The sensor units are constructed in a manner to minimize modifications for implementing different instrumentation types. However, each instrumentation sensor type requires a unique instrumentation circuit. This is accomplished by using a uniform interface for instrumentation circuit boards of all desired types. The only modifications required in the other sensor circuitry are setting the transmitter address, routing of the secondary regulator, and insertion of the wake-up circuit. This allows for developing new instrumentation monitoring types by developing a new instrumentation circuit board and eliminating redevelopment of other components.

The sensor unit's wake-up circuitry uses a laminated piezoelectronic sheet for highly sensitive vibration detection. The sensitivity is adjustable prior to potting the sensor unit. LDT series vibration detector by The Measurement Specialties Inc.[5] is used to detect any valve movements. The piezoelectronic laminate produces a voltage capable of waking the microprocessor from sleep mode without any power required from the sensor unit's batteries. This allows the sensor unit to remain in sleep mode with little power consumption but continuously monitor a valve for any events which would require its other instrumentation. This is a key element in extending the sensor unit's battery life.

The sensor unit's power regulator circuitry takes advantage of the features provided by the dual input smart battery backup regulator from Linear Technology[6]. Two of the devices are use to deliver power from four batteries. Both regulators can supply power to the entire sensor unit for extended battery operation while maintaining a seamless transfer of supplied power from each battery. When necessary, one can be routed to instrumentation providing excellent isolation for precision instrumentation and noise reduction. The regulator has a power down feature to reduce the power consumption when it is not needed. The regulator also is capable of monitoring the state of the batteries. This allows the microprocessor to appropriately manage power utilization. The battery levels are tested during the update phase of the microprocessor. A data event is transmitted to the base stations indicating required maintenance if a low state is encountered.

The temperature sensor unit utilizes a cold junction referenced thermocouple instrumentation circuit. The circuit uses a monolithic thermocouple amplifier chip with cold junction compensation pretrimmed for Type K thermocouples from Analog Devices[7]. The temperature sensor unit accepts two Type K thermocouples. The microprocessor reads in an analog signal from the thermocouple and converts it to degrees Fahrenheit. A table lookup algorithm is implemented to obtain an accuracy of plus or minus one degree Fahrenheit. The Omega Engineering Inc.[8] Type K thermocouple conversion tables are utilized in the table lookup algorithm. The unit is capable of reading temperatures from -454 Fahrenheit to 315 Fahrenheit. The unit can also be point calibrated for a specific thermocouple through the onboard programmer interface header. The unit is pre-programmed to read a temperature every sixteen seconds, and can be adjusted as desired. Once the conversion is completed a data event containing the temperature and time stamp is transmitted to the base station.

The strain instrumentation circuit is used to monitor axial, biaxial and torsional strain types. Each strain instrumentation sensor unit can read two strain types. The placement of precision resistors in the circuit denotes the circuit as a full, half, or quarter bridge foil strain gage configuration. The quarter bridge configuration monitors the single axial bonnet strain for the linearly actuated valve. The Vishay CEA-09-125UN-350 foil strain gage[9] is used in a quarter bridge configuration. The half bridge configuration monitors the same single axial bonnet strain but offers temperature compensation. The Vishay SK-09-060WT-350 foil strain gage[9] is used in a half bridge configuration. This configuration is superior when only a single axial strain can be produced, but if any biaxial strains are expected the quarter bridge configuration must be used. A 4 micro strain resolution is obtainable from the quarter and half bridge configurations. The full bridge configuration monitors the torsional strain in the high geared ball valve. The Vishay CEA-09-250US-350 foil strain gage[9] is used in a full bridge configuration. A four micro strain resolution is obtainable from the full bridge configurations. The typical ball valve requiring health monitoring uses a 2 inch solid 304 stainless rod. A 50 ft/lb torsional force on such a steel rod is accurately detectable[3].

A simple magnetic reed limit switch instrumentation circuit is use for tracking the number of valve cycles performed on a high geared ball valve. The limit switch instrumentation circuit can monitor six switches with the ability to wake the sensor unit up on two switches. The determination of valve cycles performed under cryogenic temperatures is accomplished by the base station correlating a valve cycle event with the inlet and outlet temperature. The base station keeps up with totals and generates the proper data log entry.

The signal circuit was designed to unobtrusively interface with the Linear Variable Differential Transformer (LVDT) signal from the valve's internal servo controller. It enables the sensor unit to read a 4 - 20 milliamp signal or a 0 - 10 volt DC signal for reading the valve position signal. A highly sensitive magnetic sensor reads the milliamp signal by monitoring the magnetic fields produced from the current loop. The sensors used are Giant Magnetoresistance AA series analog sensors from Nonvolatile Electronics Incorporated[10]. The voltage signal indicates the level by use of a voltage follower circuit. Utilizing these methods ensures failures in the monitoring unit will not affect the operation of the valve. The LVDT signal provides a highly accurate valve position within 0.01% of the valve stroke. Monitoring the

position changes denotes the total distance of valve travel and the number of directional changes. The monitoring system logs the accumulated distance traveled and total number of directional changes after each position's resultant travel. The fully closed valve position applies a predefined amount of load against the valve seat. This is referred to as the valve preload. As the valve seat incurs wear, the valve's closed position slightly changes reducing the preload. The valve position is monitored for any change in the closed position and generates a data event when necessary.
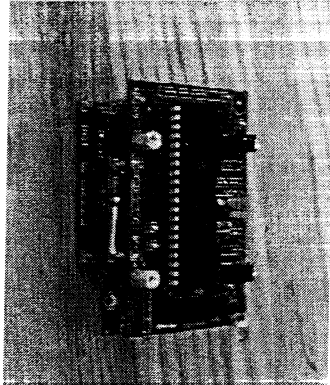
Figure 4: The un-potted sensor unit   Figure 5: The sensor unit and a potted battery pack
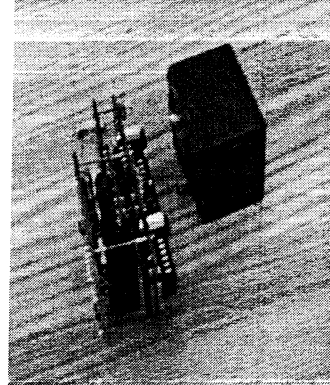
3.2 Additional attributes

The valve monitoring system must be able to meet other critical criteria to be applicable to field operation. The sensor units must be very power conservative to make them maintainable. The battery packs must last for several weeks, unlike data logging systems on the market, which typically last a few days. The sensor units are believed to last four to five weeks. The largest power consuming portion is the wireless transmission device. It must be powered down for the majority of operational time. This means a receiver on the sensor unit is not an option. A one way communication protocol must be implemented. This makes time synchronization difficult to achieve. The sensor unit and base station receiver unit both have accurate oscillators which can keep time within a quarter of a millisecond for over five weeks. The sensor unit transmits its time once a day to the base station. It only needs to perform one transmission in order to maintain accurate time synchronization. The base station keeps the previous day's time synchronization if a transmission error occurs or no transmission is made. If such an event occurs an entry into the data log is made in order to identify any data corruption due to time stamping. The monitoring system has 35 days to perform a good data synchronization link-up before any time accuracy is at risk. The base station has an IRIG-B timing module which provides a digital signal to all the base station receiver units. These units synchronize the sensor unit's time to the IRIG time. When a data event occurs the sensor unit transmits the event and its time according to an internal clock. Redundant transmissions are performed to avoid data transmission errors. The base station receiver unit converts the sensor time to IRIG time. The data event is then passed to the base station's main microprocessor which correlates any other applicable data such as inlet temperature. The refined event log is then stored in a text string on a removable flash memory card and broadcasted on an Ethernet network. The flash memory access units are made with a Compact Flash Development Kit from ARMA Design Inc[11]. The microprocessor aboard the Compact Flash board is use as the base station's main controller[5]. The data broadcasting performed by an off-the-shelf Ethernet embedded controller unit called an I-7188E Module which is manufactured by ICS DataCom[12]. The implementation of other network communication transmissions can be accomplished by using the desired communication module[6].

4. CONCLUSIONS

The valve monitoring system is a feasible solution for helping maintain high-geared ball valves and linearly actuated valves within the Propulsion Test Facilities. It helps avoid untimely failures by flagging degraded performance. However, this approach is not feasible for determining degraded operation during a propulsion test due to the highly dynamic conditions. It may take several seconds to correlate the data with an event and transmit an alert through the system. However, a considerable advantage can be obtained by monitoring valve performance over the operational life

of the valve. Post event detection can be accurately related to other events and an operational history developed. A higher level facility monitoring system would be able to automatically utilize the operational histories.

5. REFERENCES

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6. Linear Technology Corporation, www.linear.com, McCarthy Boulevard, Milpitas, CA 95035-7417.
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12. ICS DataCom "I-7188E Hardware Manual", Commerce Circle, Pleasanton, California 94588

Valve Health Monitoring System Utilizing Smart Instrumentation

Stennis Space Center

By:

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AST, Electronics Instrumentation Systems

NASA, Stennis Space Center

Engineering and Science Directorate, Design and Analysis Division

Valve Health Monitoring System
Utilizing Smart Instrumentation

- Previous testing has incurred unexpected
  - ➢ Schedule delays
  - ➢ Maintenance costs
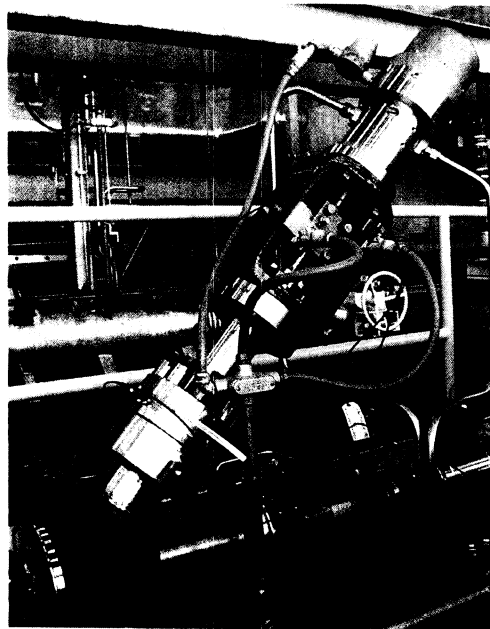
- Due to valve
  - ➢ Repair
  - ➢ Replacement

TRW 650K E1 Test Stand July 2000

Valve Health Monitoring System Utilizing Smart Instrumentation

Need to track hardware life requires implementation of monitoring systems

Linearly Actuated Valve

Valve monitoring for:

➢ High-Geared Ball Valves

➢ Linearly Actuated Valves
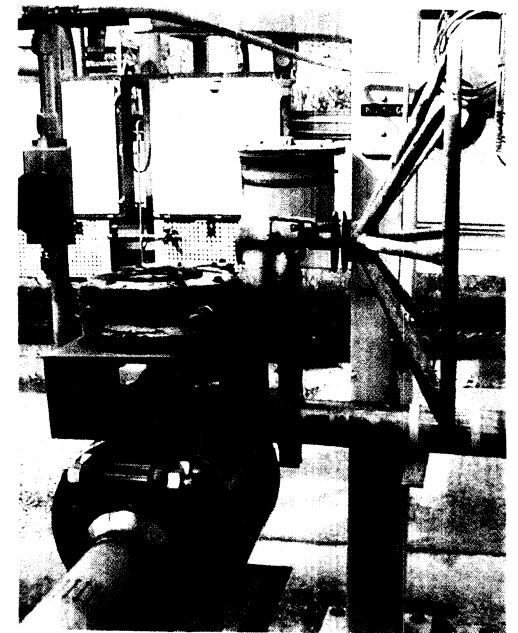
High-Geared Ball Valve

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- **High-Geared Ball Valves**

  - ➤ Torsional shaft strain
  - ➤ Total valve cycles
  - ➤ Cryogenic valve cycles
  - ➤ Inlet temperature
  - ➤ Outlet temperature
  - ➤ Body temperature

- **Linearly Actuated Valves**

  - ➤ Linear bonnet strain
  - ➤ Total linear travel
  - ➤ Total directional changes
  - ➤ Valve preload position
  - ➤ Inlet temperature
  - ➤ Outlet temperature
  - ➤ Body temperature

Sensor Placement for High-Geared Ball Valves
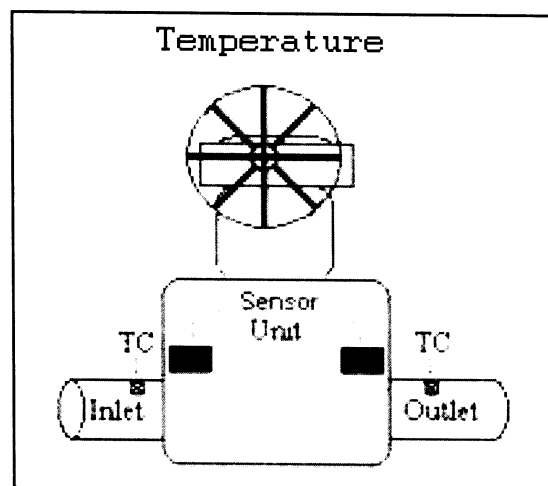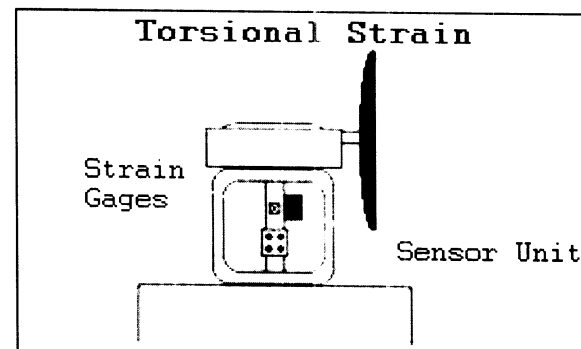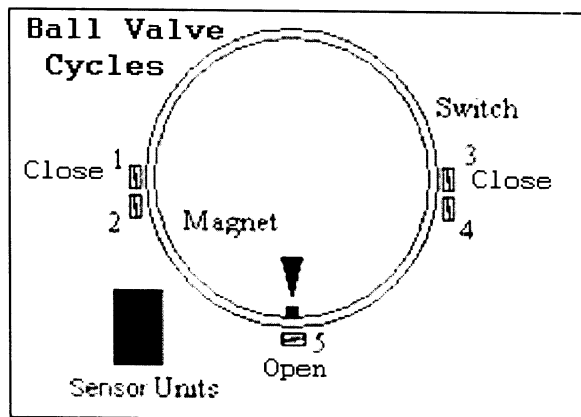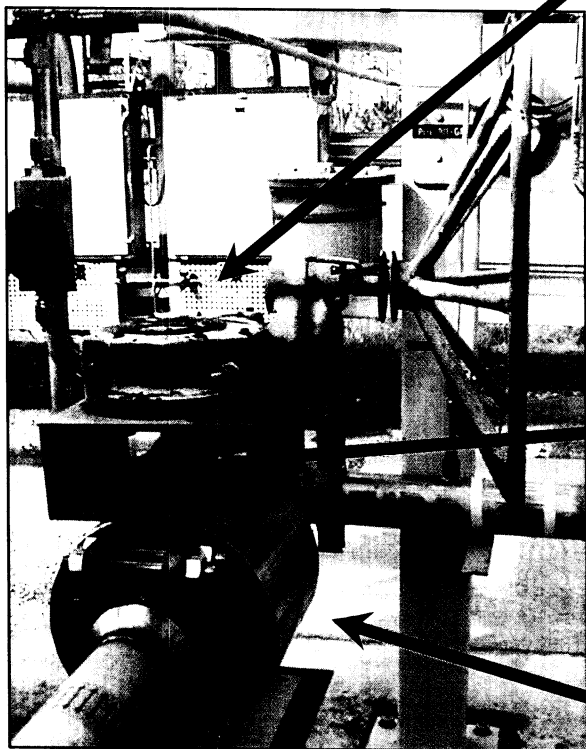
Ball Valve Cycles

Switch

Close 1

Close 3

Magnet

2

4

Open

5

Sensor Units

Torsional Strain

Strain Gages

Sensor Unit

Temperature

TC

Sensor Unit

TC

Inlet

Outlet

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Linear Strain

Sensor Unit →

Strain Gage →

Strain Gage ←

LVDT Position

Actuator Cable

Sensor

Sensor Unit

Actuator

Temperature

Sensor Unit →

Temperature Gage ↓

Temperature Gage ↑

Temperature Gage ↑

Outlet

Inlet
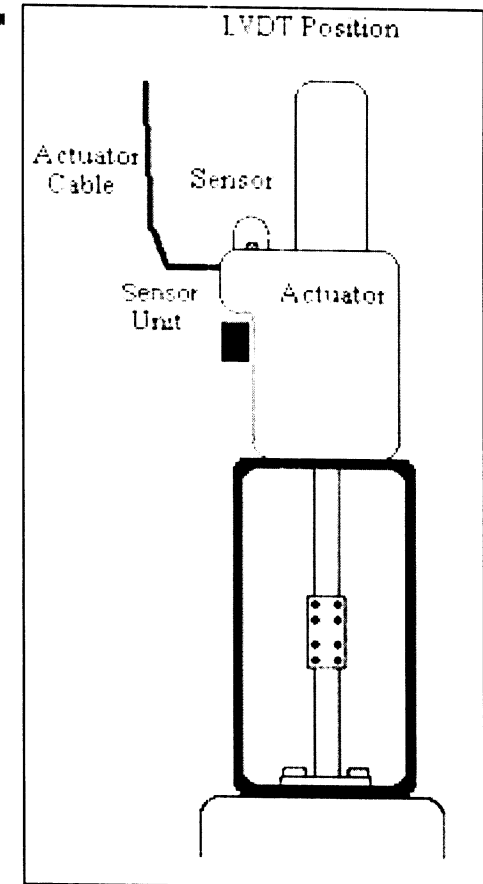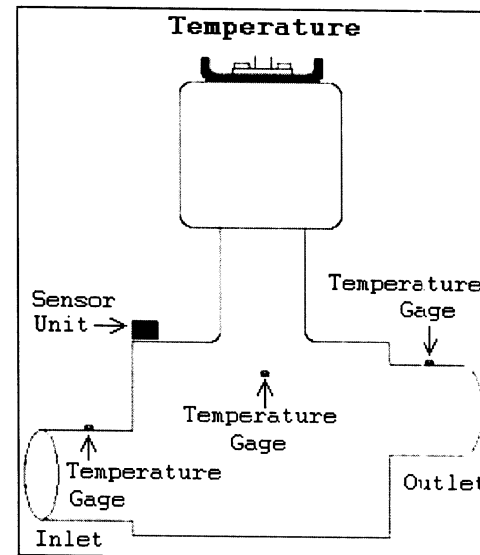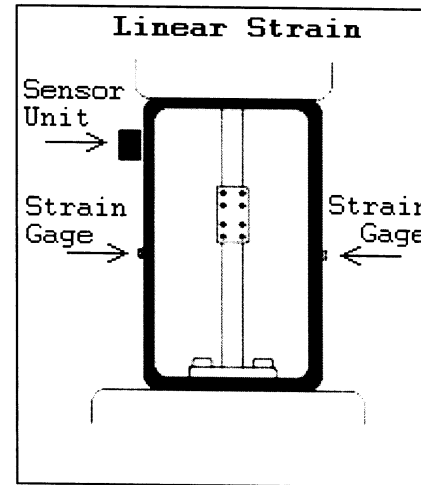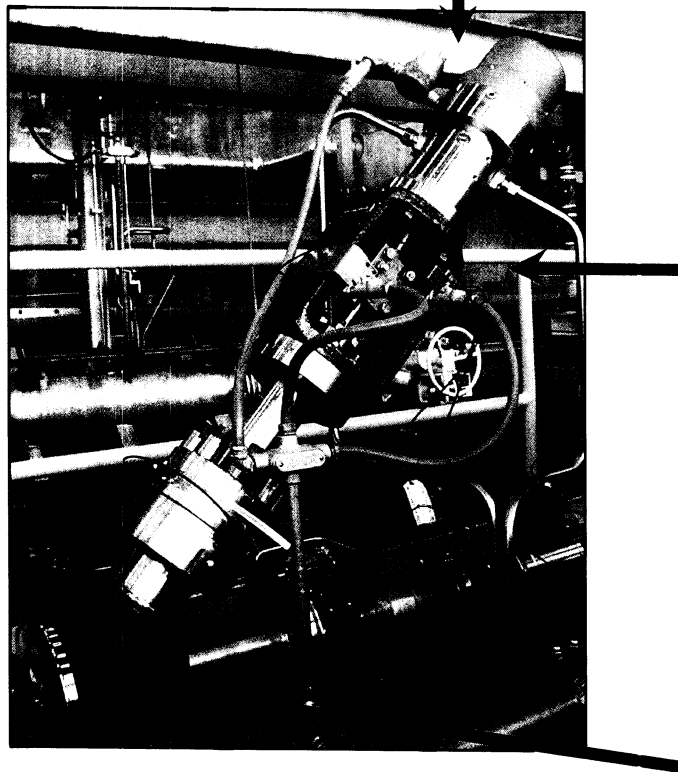
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Valve Monitoring System Fundamental Configuration
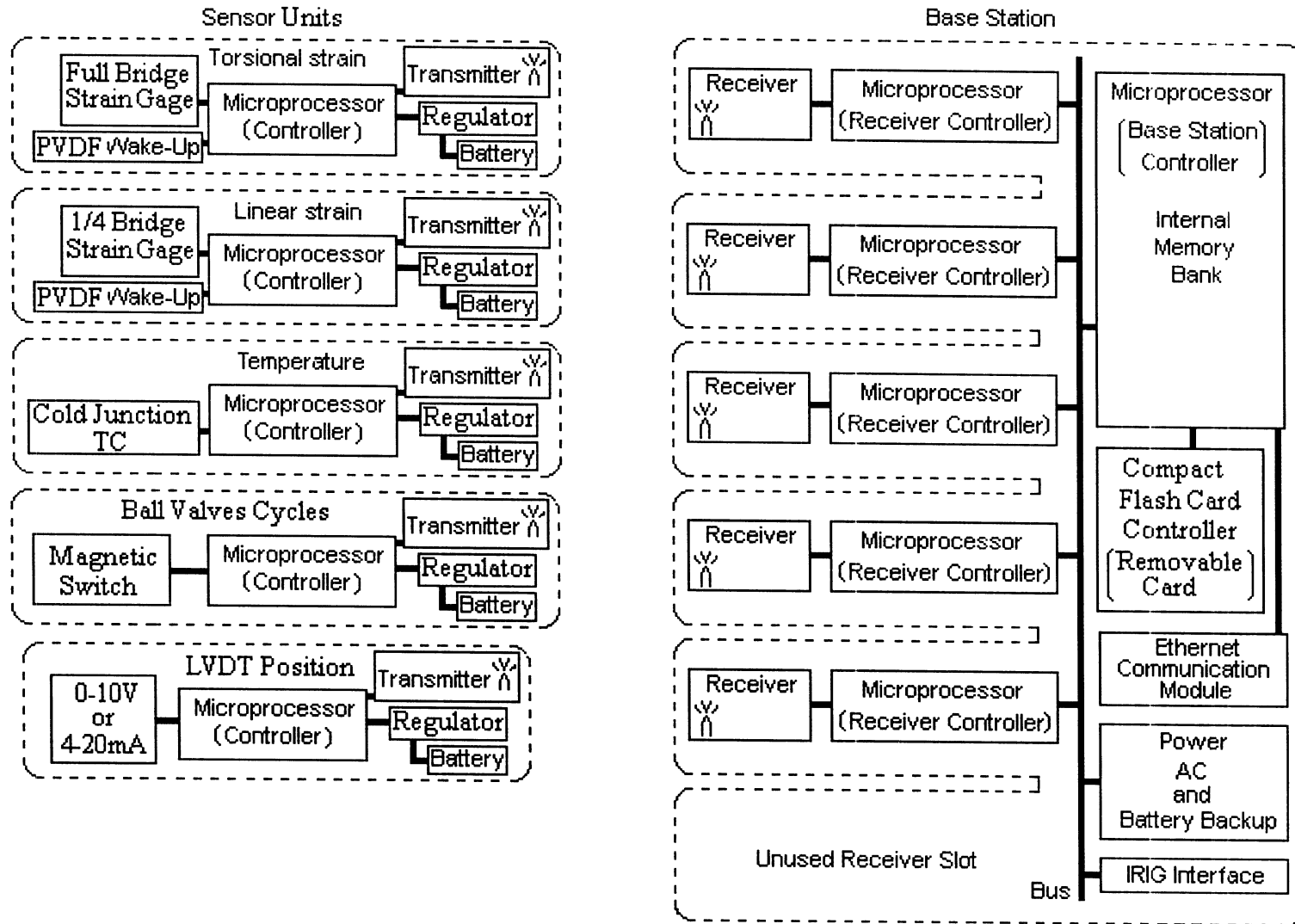
Valve Health Monitoring System
Essential Capabilities

- Operate in Confined Locations
- Safe Operation in Explosive Environment
- Extremely Low Power Consumption
- Data Correlation
- Accurate Data Synchronization
- Automatic and Manual Data Access
- Simple Setup and Maintenance
- Expandable System
- Cost Effective Manufacturability
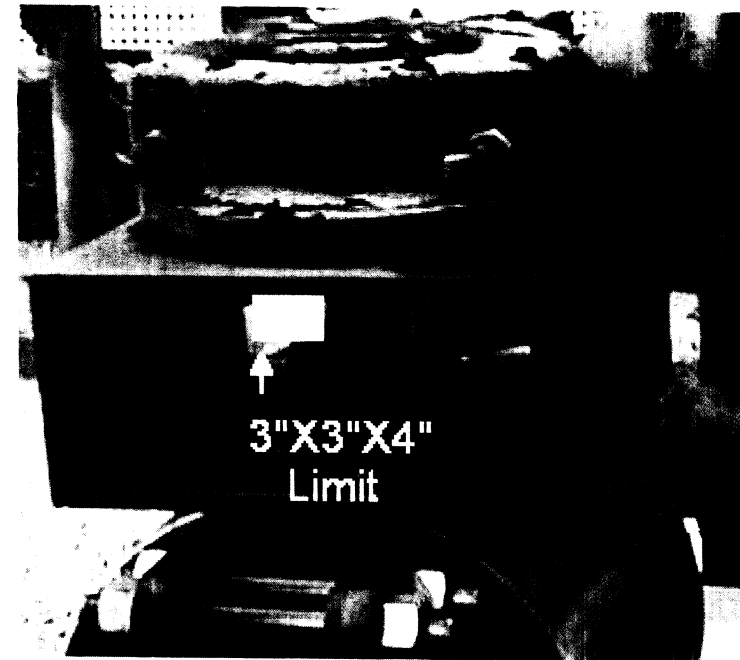- Adaptive for Future Monitoring Tasks

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Valve Health Monitoring System
Essential Capabilities

- ## Confined Locations

  - ### Sensor Size

    2½ X 3 X 4 inch

  - ### Wireless

    35 foot transmission radius

    Added data security

    902-928 MHz band

    Compliance with Federal
    Communication Commission

  - ### Battery Powered

    Two battery packs

    with two 9 Volts supplies

3"X3"X4"
Limit

Valve Health Monitoring System
Essential Capabilities

- ## NEC Class I Division II Group B Hazardous Environment

  - Compliance with NEC article 501
  - Enclosed in Potting

    Blue-epoxy flame retardant 832FRB

    M.G. Chemicals

  - Internal temperature monitoring

    Shutdown at 150° F

  - No exposed arcing points
  - Limited operational power

    9 Volts at 250 milliamp
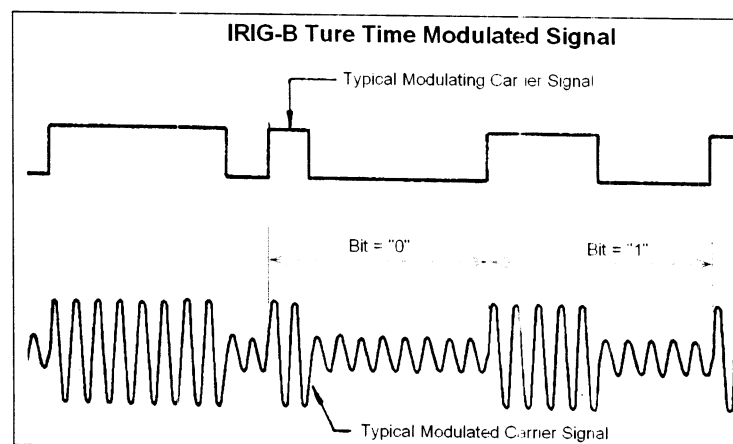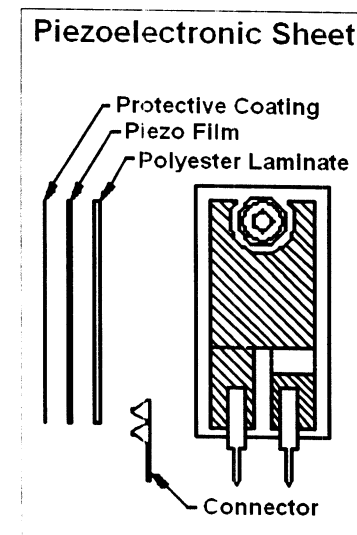
  - No exposed cavities
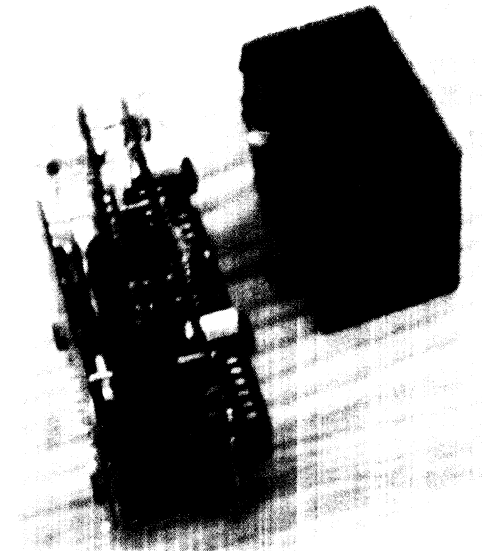
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Valve Health Monitoring System
Essential Capabilities

- # Extremely Low Power Consumption
  - ## One-Way Communications
    Linx HP3 transmitter and receiver modules
  - ## Microprocessor Sleep Mode
  - ## Piezoelectronic Wake-Up Circuitry
    Measurement Specialties LDT series

- # Accurate Data Synchronization
  - ## IRIG-B Timing Module
    Facility correlation
  - ## Communication Bus
    Internal data correlation

Piezoelectronic Sheet

- Protective Coating
- Piezo Film
- Polyester Laminate
- Connector

IRIG-B Ture Time Modulated Signal

Typical Modulating Car ier Signal

Bit = "0"   Bit = "1"

Typical Modulated Carrier Signal

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- ## Automatic and Manual Data Access
  - ### Memory Storage Network Capable
    Compact flash card memory access
    ARMA Design Inc.
  - ### Network Capable
    Ethernet broadcast I-7188E
    ICS DataCom Inc.

- ## Setup and Maintenance
  - ### Simple Human Interface
    Switch and Indicator light
  - ### On-board Programmer Interface
    Serial communications
   Software updates
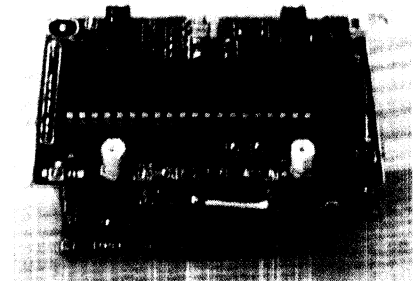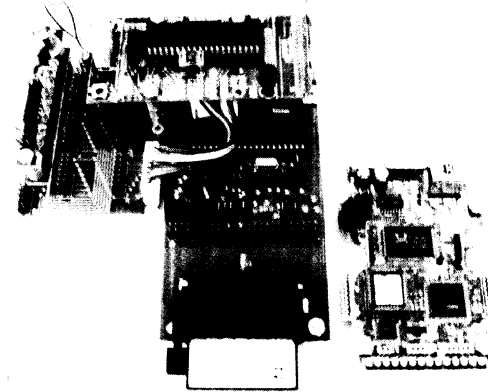
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Valve Health Monitoring System
Essential Capabilities

- ## Adaptive for Further Monitoring Tasks
  - ## Software Upgrades
  - ## Interchangeable Instrumentation Circuit
    - Each instrumentation type confined to a single circuit board
    - Normal interface allows for further instrumentation types
    - Eliminates redeveloping common components

- ## Cost Effective Manufacturability
  - ## Manufacturing Friendly
    - Common circuit board etching
    - One-sided component population
  - ## Commonality between circuits
   - Reuse of board for multiple functions
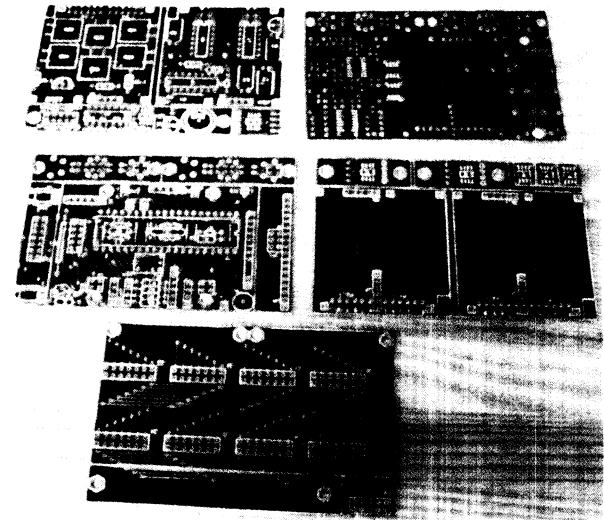
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Valve Health Monitoring System
Common Structure

- The Microchip Technology PIC16F877A Microprocessor is utilized in:
  - The Base Station controller
  - Sensor Units
  - Receiver Modules

- The main microprocessor board is identical in:
  - The Receiver Board and Main Sensor Board

- Each receiver module utilizes the identical:
  - The PIC16F877A microprocessor
  - TMP36GS temperature circuitry
  - The Linx HP3 Receiver modules

- Each sensor unit utilizes the identical:
  - The PIC16F877A microprocessor
  - TMP36GS temperature circuitry
  - The Linx HP3 transmitter model
  - Linear Technology dual battery smart regulator
  - Dual battery packs
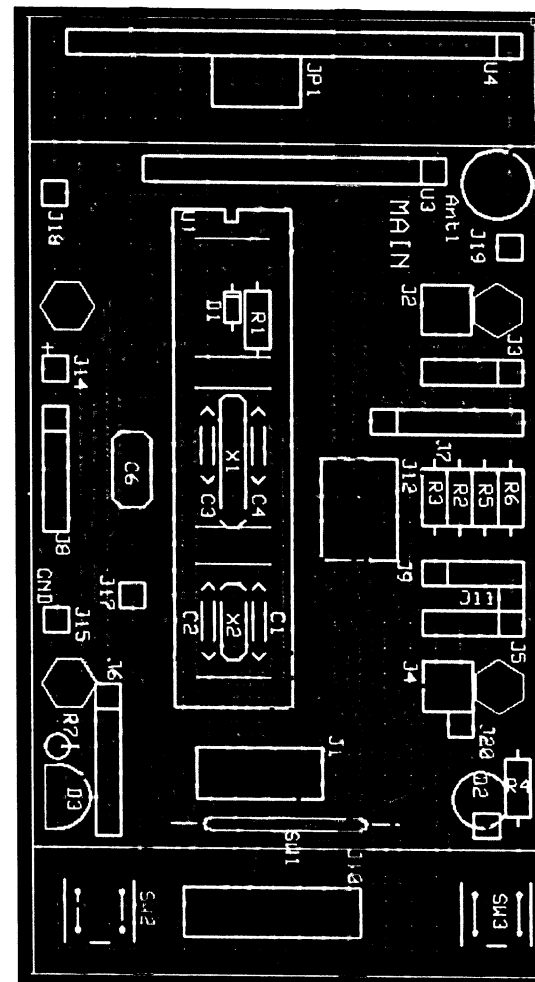

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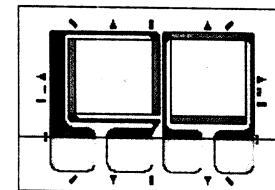# Valve Health Monitoring System Instrumentation Types

Uniaxial Pattern

- ## The Type K Thermocouples Sensor
  (for inlet, outlet, and body temperature monitoring)
  - Monolithic thermocouple amplifier from Analog Devices
  - Uses cold junction compensation

Biaxial Pattern

- ## The Strain Instrumentation Sensor
  (for bonnet and torsional strain monitoring)
  - Axial Strain by a Vishay precision quarter bridge
  - Biaxial Strain by a Vishay precision half bridge
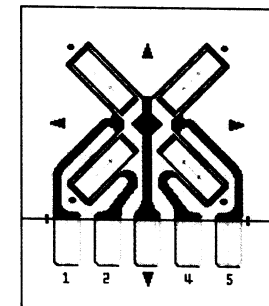 - Shear Strain by a Vishay precision full bridge
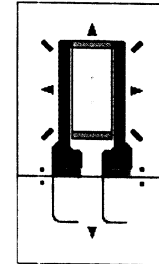
Shear Pattern

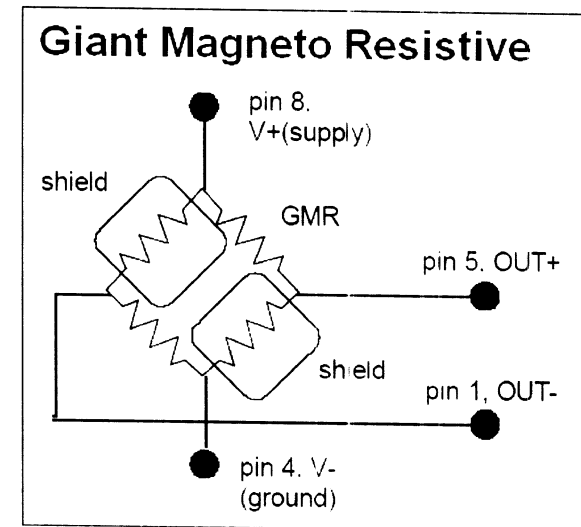# Valve Health Monitoring System Instrumentation Types

Giant Magneto Resistive

pin 8.
V+(supply)

shield

GMR

pin 5. OUT+

shield

pin 1, OUT-

pin 4. V-
(ground)

- ## Limit Switch Sensor

  (for monitoring number of cycle)

  - 6 magnetic reed switches
  - 4 inputs with wake-up capabilities

- ## Signal Interface Sensor

  (for Linear Variable Displacement Transducer Transformer monitoring)

  - 4 to 20 milliamp current loop signal

    Giant Magneto Resistive (GMR) for

    Unobtrusively monitors magnetic fields

  - 0 to 10 volts Direct Current (DC) signal

    Basic voltage follower circuit

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The system is a feasible solution

- Can help maintain high-geared ball valves
- Can help maintain linearly actuated valves
- Flags degraded performance
- Generates operational performance history
- Able to be Integrated into a higher level health monitoring system

- Not a feasible detection system during a test

Questions

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Valve Health Monitoring System
References

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- Measurement Specialties Inc., www.meas-spec.com, Lucas Way, Hampton, VA 23666.
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- Analog Devices Corporation, www.analog.com, P. O. Box 9106,One Technology Way, Norwood, MA, 02062-9106.
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- Vishay Measurements Group Inc., P.O. Box 27777, Raleigh, NC 27611.
- NVE Corporation, www.nve.com, Valley View Road, Eden Prairie, MN 55344-3617.
- ARMA Design "Compact Flash Card Development Kit Manual", Ferris Square, Suite E, Sand Diego, CA 92121.
- ICS DataCom "I-7188E Hardware Manual", Commerce Circle, Pleasanton, California 94588.

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