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Multi-Sensor Architecture Development for Intelligent Systems

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Multi-Sensor Architecture Development for Intelligent Systems

by

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Abstract

Multi-Sensor Architecture Development for Intelligent Systems

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The philosophy of research at the University of Texas – Robotics Research Group (RRG) is towards creating a foundation for an open architecture, reconfigurable intelligent machines to meet wide breadth of operational needs. An intelligent system is the one which has complete knowledge of its operating characteristics at all times (updated in real-time) and it can make on-the-fly decisions to adapt itself to the different conditions or present the best possible options to the human decision maker under specified and ranked criteria. The reality of all complex system is that they are inherently non-linear with coupled parameters. The traditional approach dealing with such systems assumes linearized models, imposing conservative bounds on the operational domain and thus limiting performance capability of the system. Recent advancements in sensor technology and availability of computational resources (embedded processing) at low cost have made real-time intelligent control feasible for complex systems. The computational intelligence envisioned in modern intelligent machines will enhance the system performance and will provide capabilities such as criteria based control, identification of incipient faults, condition based maintenance, fault tolerance, and ability to monitor performance parameters in real-time. The first step in this process is to equip a system with a comprehensive suite of sensors. These sensors will provide real-time data and awareness about both, the internal system states and the external/environmental operating conditions. The aim of this work is to establish an argument in favor of using multiple sensors in all complex electro-mechanical systems. The report discusses numerous benefits of a multi-sensor environment with suitable examples and attempts to justify its pressing need in all the existing complex mechanical systems. Case studies for a multi-sensor environment in railroad freight cars and vehicle systems are presented. Sensing requirements in freight train and vehicle systems are evaluated and suitable sensor technology and commercial sensor options are suggested for decision makers. In addition to benefits, challenges in a multi-sensor environment such as sensor noise, cabling complexities, signal processing, communication, data validation and data management, sensor fusion, information integration, maintenance etc. are addressed and best practices to alleviate these complexities are discussed in the report. This effort lays out a foundation for developing a multi-sensor system and will enable computational intelligence and structured decision making in the system.

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Chapter 1: Introduction

1.1 BACKGROUND

The emphasis in the scientific community in 21st century will be to build upon the past breadth of applications in the discipline of mechanical engineering with the recent advancements in sensing and computing technology (hardware and software) to develop a completely modern science base for intelligent machines. The intelligent machines are not intended to replace humans, but augment their capabilities and reduce human drudgery and thus enhancing the relationship between man and machine. This has been the philosophy of research at the UT Robotics Research Group (RRG), to create a foundation for an open architecture, reconfigurable intelligent machines to meet wide breadth of applications/operating needs under direct human oversight. Emphasis in this direction will create a next wave of technology [Tesar, 2009] which will modernize all the existing mechanical systems (automobiles, aircrafts, ships, manufacturing and construction equipment, household appliances etc.)

The next wave of technology for intelligent machines will be made of two major components. The hardware component consists of actuators and sensors. Electro-Mechanical actuators will be the heart of the intelligent system. Multiple sensors will be used to assess real-time information about both, the internal system states and the environmental operating conditions. Actuators and sensors together constitute a dexterous system. The software component will impart intelligence to the system. It will enable intelligent control of these dexterous systems under direct human command and oversight (for example, emerging field of robotic surgery). The universal software component will provide optimal options for maximizing performance (performance criteria and norms by the human operator), condition based maintenance for timely repair (continuous system monitoring and plug-and-play components for replacement), and fault tolerance (online recovery from a fault and continued operation) [Tesar, 2009].

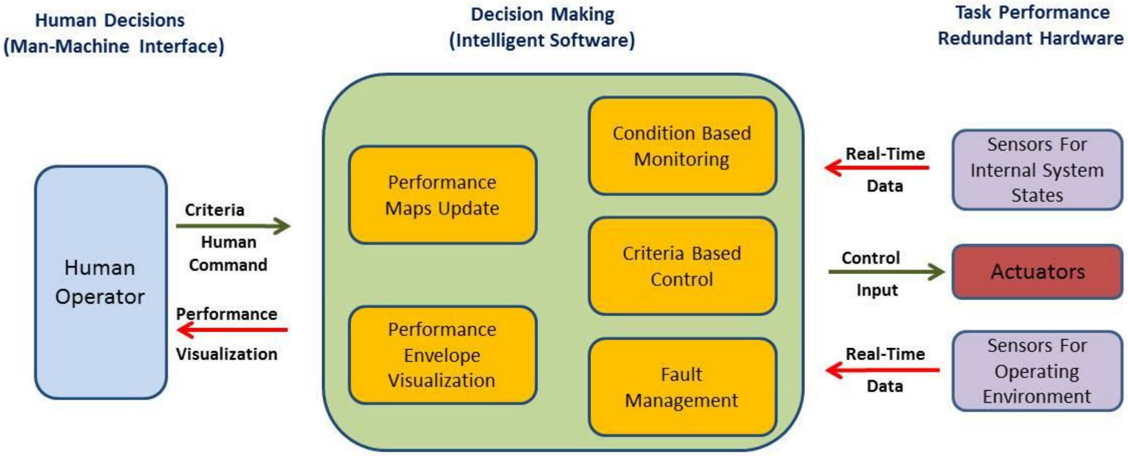


Figure 1-1: Overview of Intelligent System

In the system development, significant amount of research has been carried out and continues towards development of advanced actuators. Actuator designs have been proposed for a range of applications including battlefield vehicles and general industrial robots [Tesar, 2005]. Figure 1-2 shows a prototype of an elbow actuator for a rugged manipulator.

Figure 1-2: Rugged Actuator Prototype [Tesar, 2005]

Naturally, the next step is to delve into the development of sensors and multi-sensor architecture. The goal is to maximize performance of the system under human command. Increasing demand for performance requires full awareness of the system's condition and response capability which can only be achieved by means of multiple sensors/measurands. Sensors will provide real-time data and awareness about both, the internal system states and the external/environmental operating condition. Data from multiple sensors can be fused to obtain useful information for the decision maker in real-time. Sensor data will also be used to update performance maps of the components and condition based maintenance of the system.

The UT Austin's Robotics Research Group has developed a visualization based framework for decision making in an intelligent multi-input multi-output system using performance maps and envelopes. Sensor information is the basis for such an informed decision making process where a maximum performance decision surface (scenario) is generated and presented to the human-computer decision making system using current operating conditions and defined operational criteria.

1.2 INTELLIGENT SYSTEMS

An intelligent system is the one which has complete knowledge of its operating characteristics at all times (updated in real-time) and it can make on-the-fly decisions to adapt itself to the different conditions or present the best possible options to the human decision maker under specified and ranked criteria. Intelligent systems should essentially have following characteristics.

1 **Reprogrammability and Reconfigurability:** Reconfigurability refers to ease of hardware and software modifications. An intelligent system will be made up of standardized modular components. This results in easy replacement or upgrade of the components based on customer demands. Software reprogrammability allows easy change in the control scheme of the system based on changing operating criteria.

2 **Fault Tolerance:** Fault tolerance is the system's ability to continue operation under a fault. Redundant resources are the keys to a fault tolerant system. Redundant resources can be in the form of an analytical formulation - where a theoretical/analytical relationship is used to infer the lost data; or hardware redundancy by having more than one component (sensors or actuators) in parallel. For example in a battle field vehicle with 18 independent multi-speed drive wheels if one actuator fails, seventeen other actuators working in parallel can compensate for the failed actuator to keep the vehicle performing.

3 **Utilization of performance maps and envelopes to maximize performance:** A performance envelope is a surface in the decision parameter space (mostly 3 dimensional) representing the best or worst attainable condition under the given current condition. An intelligent system should ideally have many low cost sensors to

get the complete awareness of the operating condition and system states. Each system component is represented by carefully acquired certified performance maps which can then be combined into performance envelopes [Ashok and Tesar, 2008]. These envelopes become decision surfaces to be presented to the human-computer decision making system to make informed decisions to maximize performance [Ashok and Tesar, 2010].

4 **Criteria Based Control:** User set priorities and user defined performance criteria are used to compute the control input to the system. These criteria include better efficiency, faster speed or higher torque for actuators, disturbance and shock rejection etc.

5 **Condition Based Maintenance:** Condition based maintenance algorithm in the intelligent system continuously monitors the performance at the component level and system level to identify incipient failures. It provides timely warnings about malfunction enabling preemptive maintenance, enhanced availability, reduction in false alarms, reduced down time and thus reduction in overall maintenance cost and speed.

6 **Ability to monitor coupled non-linear property:** Any complex system exhibits highly non-linear behavior due to coupling/dependence between the system parameters. An intelligent system will have multiple sensors to get direct information about these coupled parameters and hence have a total awareness about the state of the system in real-time. This information in combination with appropriate decision making criteria will enable the system controller to extract the best possible performance from the system to match ever changing objectives. In addition,

information from the sensors can be used for condition-based monitoring of the components.

1.3 NEED FOR MULTI-SENSOR INTELLIGENT SYSTEM

The reality of all mechanical systems is that they are inherently non-linear. That nonlinearity enables their wide flexibility in task performance in the form of their multiple distinct output functions. Traditional methods for control of these mechanical systems involve developing a theoretical (mathematical) model of the system where the system behavior (response) is characterized by a set of differential or partial differential equations. Such an approach may work fine in the case of the simplest systems but it breaks down for inherently non-linear, more complex, multi-input multi-output systems. In addition to non-linear coupling between the system parameters, system operation is also sensitive to the operating environment parameters (such as temperature, magnetic field for an actuator and terrain condition for vehicle operation). A direct analytical relationship between the environment parameters and the system output may be very difficult to realize and the unmodeled effects may ultimately dominate the system performance. Even when the analytical relationship exists, their inclusion in the mathematical model results in a highly complex coupled formulation unsolvable by continua mathematics. For example a railroad car truck requires up to 41 parameters to provide a highly non-linear description of the actual physical response to a wide variety of track-based inputs (track width/centerline variation, track tilt, vertical motion etc.) [Sankar, 1987]. This non-linearity means there is no general solution using classical control methods. Analytical models tend to neglect these important parameters in favor of simpler linearized formulations.

The linearized models of the system impose conservative ranges on the operational domain limiting performance capability of the system. For example an electro-mechanical actuator in practice operates under the manufacturer’s rated specifications. These specifications are conservatively estimated as there is little awareness about the actual operating condition (temperature, magnetic field saturation etc.). Lack of awareness is because none or minimal sensors are used to assess the information about the current state of the internal parameters. An intelligent actuator embedded with sensors as proposed in [Krishnamoorthy, 2005] can push the conservative performance limits during short periods of demand (Figure 1-3) and thus be able to respond to a wider range of operating conditions and duty cycles.

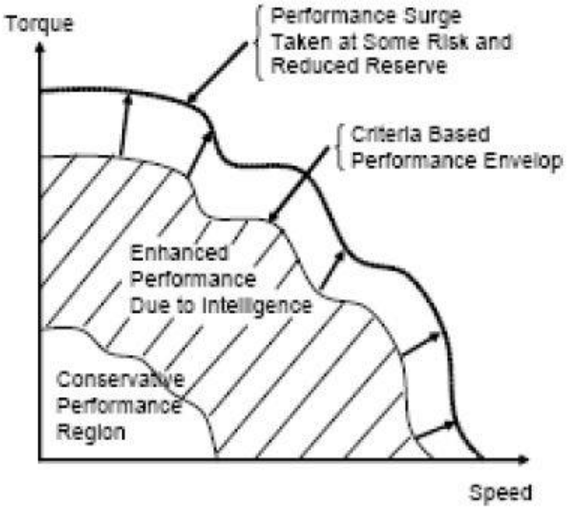


Figure 1-3: Conceptual performance envelope for an actuator [Yoo and Tesar, 2004]

Another example is an Electric Vehicle (EV) battery system. Automakers currently do not allow their EV batteries to be charged all the way to avoid possible high voltage level for safety and risk of degrading battery material. This conservative approach and built-in safeguard are to compensate for the lack of real-time information about what is happening inside the cells during operation (temperature, chemical composition, mechanical strain, voltages at each electrode etc.). These important conditions are sometimes inferred through external current and voltage readings. The uncertainty of these inferences means that batteries must be oversized significantly to guarantee reliability and safety. Palo Alto Research Center with the US Department of Energy’s Advanced Research Projects Agency-Energy (ARPA-E) is developing a small fiber optic sensor system (Figure 1-4) to measure cell internal conditions with unprecedented accuracy, allowing designers to more fully use battery’s true capabilities while simultaneously improving safety.

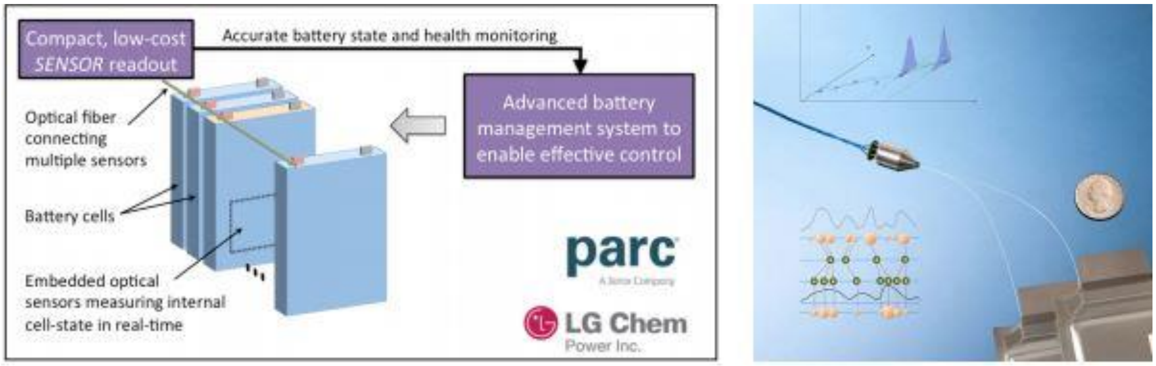


Figure 1-4: PARC Fiber Optic Battery Sensing System [www.parc.com]

Hence what is needed is a more direct approach and awareness about the system. Numerous sensors are needed to judge the operating conditions, to monitor the actual parameters and develop a more complete view. In the past, the ability of the system to respond intelligently to unstructured environments was restricted by its capability to accurately sense and interpret its operating condition. The sensing technology simply didn’t exist (immature) or was not available in small volume feasible to integrate into the system. Custom sensors were developed catering only to a particular system but these were expensive and didn't allow use in multiple systems. Multi-sensor systems also add complexity to the system which requires data management and selection of the best possible options in real time. Computational capabilities to deal with multi-sensor data were not sufficient or were not available at low cost.

But in last 5-10 years sensor technology has increased remarkably. Sensors are available with embedded computational capabilities in low cost and small size. This surge in technology has made sensing and processing wide range of phenomenon possible in real-time. Hence a new approach to intelligent control is needed which uses the actual data from the deployed sensors in real-time and caters to the performance requirement of the user. The roots of this kind of criteria and sensor based control approach can be found in the research of redundant manipulators where kinematic redundancy (extra resources) is exploited to achieve tasks like obstacle avoidance, increased dexterity etc. Criteria can also be used to measure system performance. Figure 1-5 represents a lay out of criteria based control of intelligent actuator [Krishnamoorthy and Tear, 2004].

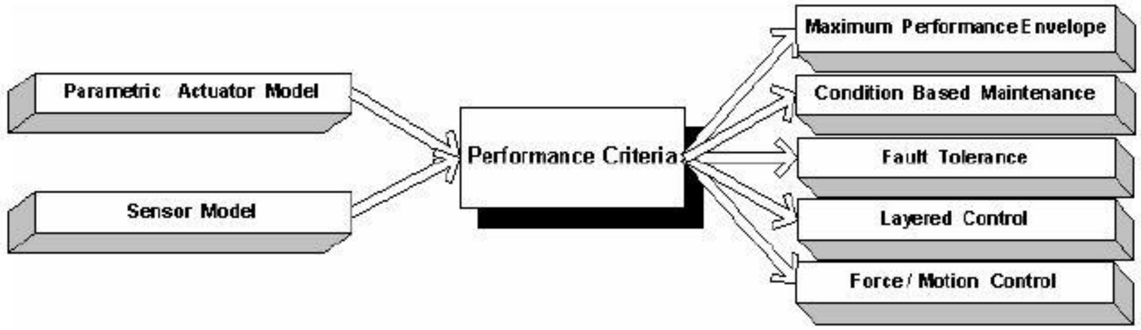


Figure 1-5: Criteria Based Control of Intelligent Actuator [Krishnamoorthy and Tesar, 2004]

A sensor model based on real-time data is essential in the criteria based control of an intelligent system (an actuator in this case) as it accounts for unmodeled effects and drift in the parametric model of actuator. The actuator model is obtained through analytical relationships or thorough metrology. A combination of the sensor model and the analytical actuator model can help achieve user specified performance goals.

One of the arguments against using multiple sensors is that addition of each sensor is a possible single point failure. But single point failures can be easily resolved using redundant sensors; either directly measuring the same phenomenon or measuring a different phenomenon which has well established analytical relationship with the desired phenomenon. These analytical information networks (e.g. Bayesian Network) can be used to infer lost data. This forms the basis of fault tolerance and fault detection and management by intelligent software. For example a railroad bearing can be equipped with a vibration sensor (accelerometer), a temperature sensor and a microphone. Failure in a bearing could be indicated by characteristic changes in the data from any of these three sensors. If say, an accelerometer fails itself, then temperature data and microphone data can be used to verify if it is an actual bearing failure or failure in one of the sensor (accelerometer in this case). This forms the basis of sensor process fault identification and management. The UT’s Robotics Research Group has shown sensor process fault management using Bayesian Networks in a multi-input multi-output system [Krishnamoorthy, Ashok, and Tesar, 2010] with theory and backed by its application in electro mechanical actuators. This technology can be successfully used to avoid single point failures and reduce false alarms in multi-sensor systems.

1.4 REPORT OUTLINE

Chapter 1 introduced philosophy of modern intelligent systems and described the characteristics desired in an intelligent system such as reconfigurability, fault tolerance, condition based maintenance, total awareness of system states and operating conditions, criteria based control etc. It discussed shortcomings of the conventional control methods and outlined the need of a multi-sensor environment in complex electro-mechanical systems.

Chapter 2 discusses various benefits of a multi-sensor environment. It lays out steps in the process of creating a multi-sensor architecture for a system. Desired sensor attributes and practical considerations in selection of sensors for a given system are discussed. It also provides examples of multi-sensor systems proposed in the past.

Chapter 3 discusses multi-sensor environment for railroad cars and freight trains. As a mechanical system trains are remarkably complex system having many components (possible single point failures) and highly non-linear coupled parameters. Chapter 3 discusses current methods of wayside sensing, discusses their shortcomings and proposes onboard sensors for real-time monitoring of train components and operational conditions. A list of desired sensors, potential sensing technologies and their use in railroad environment, and commercial sensor options are presented in the chapter.

Chapter 4 is a case study for vehicle systems. Similar to railroad cars, sensing requirements for intelligent vehicle operation are evaluated and suitable sensor technology, current state of the art and commercial sensor options are suggested for improving performance and safety in modern vehicles.

Chapter 5 addresses challenges encountered in implementation of multi-sensor environment for a given system. Sensor issues such as degradation of signals, cabling complexities, sensor noise etc. are discussed and best practices to alleviate these complexities are presented. The chapter also discusses data validation techniques, sensor fusion and data management, and efficient information flow in a multi-sensor system.

Chapter 6 summarizes the entire report. The sensors are ranked based on their importance (need), maturity level, cost etc., and are presented in a tabular format. An emphasis is made on developing a working prototype of a multi-sensor system to demonstrate ideas presented in the report.

Chapter 2: Multi-Sensor Architecture Development

Chapter 1 presented why there is an immediate need to modify all the existing complex mechanical systems in favor of more intelligent systems, equipped with multiple sensors for informed decision making and intelligent operation to meet increasing performance demands. It is a goal of this report to make an argument to create a multi-sensor environment for complex mechanical systems.

2.1 BENEFITS OF MULTI-SENSOR ENVIRONMENT

The advantages of multi-sensor systems are innumerable, some of which are presented below.

- Intelligent control in real-time using multi-criteria decision making: Mechanical systems are getting more complex to respond to human demands of increasing output functionalities and increasing performance. Non-linearity in a system will provide for complex and changing output functions (a multi-input multi-output system), but classical control methods cannot manage this complexity and deal with the inherent uncertainty in the system's operation. A system equipped with multiple sensors will provide better awareness about its state and the operating conditions reducing uncertainty and guesswork from the system control. Then there is a question about uncertainty in the data provided by these sensors but sensor data uncertainty can be reduced in a multi-sensor environment using sensor fusion techniques and fault tolerance. A multi-sensor system will enable intelligent control in real-time to extract the best possible performance from the system to match ever changing objectives.

- Enable operation under enhanced performance envelope: Many times specifications for a system operation are conservatively estimated due to lack of real-time awareness about the states and the internal parameters during the operation of the system (for example temperature, magnetic field saturation etc. in an actuator). This results in underutilization of the system and imposes a limit on the system performance. A multi-sensor system with an extensive sensor suite will provide a better awareness about the system during the operation which will enable enhanced performance and even the ability to occasionally push beyond their performance limit for a short period of time during emergency without endangering safety of the system (Figure 1-3).

- Condition Based Maintenance: A multi-sensor environment will allow continuous monitoring of system components. Continuous monitoring can enable timely detection of the component degradation and signs of impending failures which helps in preemptive maintenance. Hence a multi-sensor system will provide enhanced availability, reduction in false alarms, reduced down time and thus reduction in overall maintenance cost and speed. Condition based maintenance leads to best performance of the system in terms of safety and reliability. Figure 2-1 shows simulation flow chart of condition based maintenance in electro-mechanical actuators [Hvass and Tesar, 2004].
- Metrology: A multi-sensor system can help in understanding the effects of operating conditions on the system states. A mapping between measured data can provide empirical relationships among system parameters over changing operating conditions. Measured data can also be used to update the performance maps previously obtained through analytical relationships or experimentation. This helps in refined parametric modeling of the components and the system for future use.

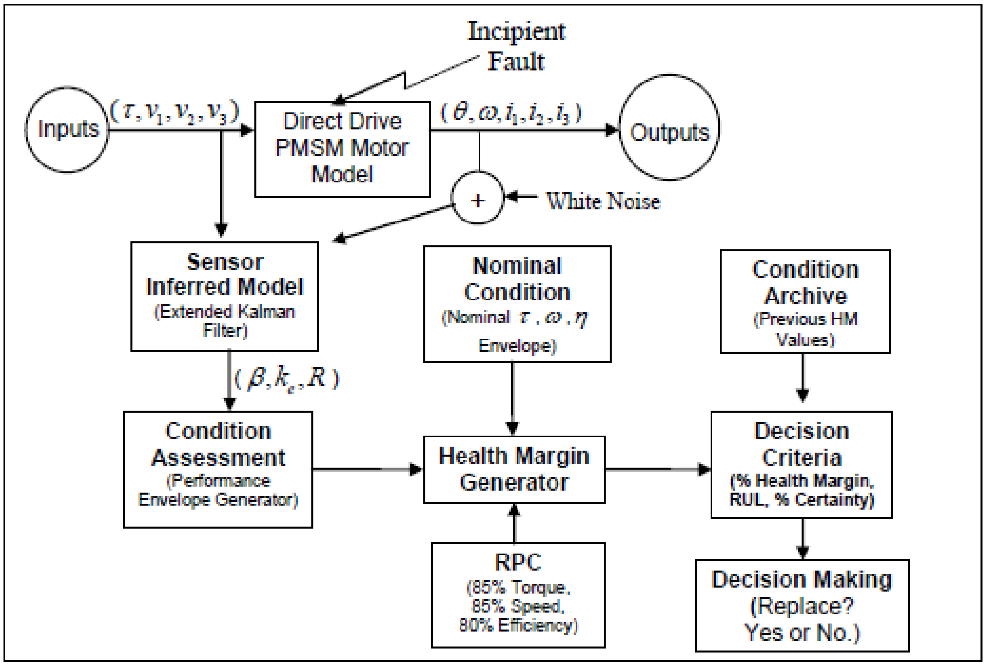


Figure 2-1: CBM flow chart in Electro-Mechanical Actuators [Hvass and Tesar, 2004]

- Effective implementation of distributed control: A distributed control structure is where each system component/sub component is controlled by a local controller which provides instructions for the operation of that component. The entire system of controllers is connected by networks for communication and monitoring. Distributed control architecture gives advantages of flexibility and modularity/reconfigurability at the system level. This means that control at the component or subcomponent level can be changed without affecting or making changes in the system level controller. For example in case of the actuator, a lower level controller uses multiple embedded sensors to dynamically optimize the actuator performance. Only results are relayed further to a higher level main controller. The higher level (system level) controller is responsible for sending commands to the lower level controllers based on user set criteria and ever changing operating conditions. A multi-sensor system will provide benefits of distributed control where the local controller will have full knowledge of its connected component's real time operating conditions.

- Operational fault tolerance: Multiple sensors will provide redundant information. This redundancy can be exploited to reduce the uncertainty in the data and provide fault tolerance in the system. For example failure in a railroad bearing equipped with a vibration sensor (accelerometer), a temperature sensor and a microphone can be corroborated from the data from all three sensors. If it is instead the case of a sensor failure, two remaining sensors can still verify normal working of the bearing to keep the system operational. Hence a multi-sensor system eliminates single point failures and provides fault tolerance.

The above discussion clearly suggests the need to include a suite of diverse sensors in complex mechanical systems for many potential gains. Many sub-systems such as automotive internal combustion engines and railroad locomotives have already deployed multiple sensors and their increase in performance and efficiency is apparent. Naturally, the next step is to advance this success to other systems. Although the sensor question is very application specific, a general approach is needed towards development of a multi-sensor system. The key questions to be addressed are: What are the types of sensors and their attributes needed, where should they be located and how will they help in augmenting the system and its intelligent control?

2.2 MULTI-SENSOR ARCHITECTURE DEVELOPMENT

The general steps in the process of development of a multi-sensor architecture are outlined in this section [Krishnamoorthy and Tesar, 2005]. Examples of steps in the development of sensor architecture in electro-mechanical actuators are given to better understand the development sequence.

2.2.1 Assessment of Requirements

The first step is to find the critical parameters in the operation of a system. A comprehensive list of various operating conditions (affecting parameters) and possible modes of failures may help in defining the scope for the types of sensors needed. A non-linear system will have various coupled parameters influencing the operation of the system. Direct measurement and real-time awareness of those parameters might be important for the intelligent control and enhanced performance. For example in case of the electro mechanical actuators, power parameters (torque/speed, voltage/current) influence the operation parameters (mechanical/electrical time constants, bandwidth etc.) and operating environment parameters (temperature, magnetic field etc.) and vice versa. A review of the extent to which these nonlinear phenomena affect the overall behavior of the system can help determine the sensing requirements. Some parameters are essential to make informed judgments in intelligent control where as others are supplementary, yet important for benefits like fault tolerance, metrology and better understanding of the system.

2.2.2 Translating High Level Requirements to Sensor Specifications

Once the sensing requirements are established, the next step is to decide suitable specifications for the sensors. Specification includes hardware parameters such as size (volume), weight, housing ruggedness etc. and sensing attributes such as required resolution, accuracy, sensitivity etc. Hardware specifications are relatively easy to define whereas measurement attributes are specific to each sensor. Specifications should be as practical as possible with considerable thought to cost vs. effectiveness of the sensor. For example, position sensors can have resolutions from a few degrees to a few seconds of an arc. Such a high resolution may not be essential for a given application and may increase cost vs. benefits of the sensor.

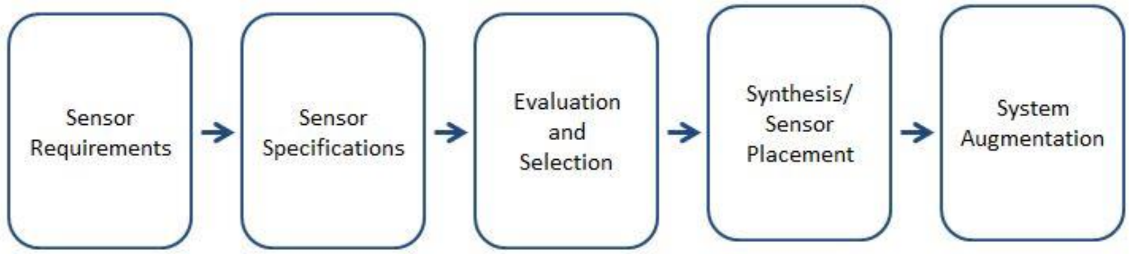


Figure 2-2: Multi-sensor architecture development process

2.2.3 Evaluation and Selection of Potential Technologies

Once the desired sensing specifications are defined, different sensors based on a variety of sensing technologies should then be considered. Various sensing phenomenon can be used for measurement of a physical quantity. For example the output angular position for an electro-mechanical rotary actuator can be sensed using Hall Effect sensors, or optical encoders or even potentiometers. A particular technology may be more suitable than others in the required sensing environment and the operating conditions. For example the Hall effect sensor may not be suitable in a place where there is magnetic field present in the surrounding, in which case an optical sensor may be a better option. Evaluation and selection of the sensing technology also depend upon the physical space available for mounting a sensor with that technology and the desired sensing requirements such as resolution, accuracy, reliability etc. A comprehensive list of all the feasible sensing technologies with their pros and cons in the required application can make the evaluation and selection process more approachable.

2.2.4 Synthesis (Sensor Placement)

Synthesis in a multi-sensor architecture context refers to combination of all the selected sensors and process of their arrangement in the system. It is a critical step since the aim is to arrange the components in a compact package. This might ultimately be a standard sensor array for a given application. Commercial sensors can be stripped down to only required/functional core and strategically arranged to get an optimal design. Sensors in the same sub system are connected to the local controller (distributed control) which may in turn be connected to a central controller. The idea is to standardize communication interface and utilize common wires for multiple sensors to alleviate cabling complexity. A careful systematic approach in the synthesis phase results in numerous benefits when the system is operational such as noise elimination, optimized data flow, and simplified hardware debugging.

2.2.5 Augmentation

A carefully selected suite of sensors and their thoughtful geometric placement should realize benefits listed in the argument for using a multi-sensor system. After the deployment of multiple sensors, the next step is to develop a platform for augmenting the system capabilities. An intelligent decision making framework based on real-time sensor data should be created which enhances the system performance. Condition Based Maintenance can be implemented for the system components. A framework for the operating software should be developed to facilitate features like generation of performance maps and envelopes, criteria based control, fault detection and sensor process fault management.

2.3 SENSOR ATTRIBUTES

The selection of a particular sensor for the system depends upon the functional requirement, and the constraints on the sensing technology. For example, a Hall effect sensor may not be suitable where there is magnetic flux present in its immediate surrounding; in which case an optical sensor may be a better option. Geometry and available space also have significant bearing on the sensor selection. There is often a compromise between the sensing requirements and the feasible options available. Custom sensors can be developed but it results in higher costs. Hence *the practical approach would be to evaluate the feasibility of off-the-shelf components (sensors) first and delve into the custom development only in unusual cases.*

Sensing requirements and desired attributes in a sensor change from application to application. But in general there are some basic characteristics desired in all the sensors. These attributes play an important role in the evaluation and selection of a particular sensor among all the suitable options. The attributes include hardware features, sensing/measurement principles and data processing, data transmission properties. The following list gives the description of certain basic characteristics that all the sensors can be judged on.

2.3.1 Hardware Attributes

- **Ruggedness and durability**: The sensor should be able to perform in all operating conditions of the system which may necessitate sensor operation in harsh environment, weather proofing, strong housing material. It is an important factor in long life of the sensor.

- **Operating Temperature Range**: Sensor should be functional in a wide range of operating temperature range. Sensing phenomenon may be sensitive to the temperature, in which case temperature compensation is provided in many sensors.
- **Ease of integration**: Sensor should have easy mechanical assembly in the system. It is desired to have standard electrical connections, plug and play interfaces and modular hardware.
- Sensors should be **small in size, light weight** and should have minimal sub-components. Sensors should have little effect on the phenomenon they measure or to the structure to which they are attached, for example a torque sensor serially attached to the shaft may add compliance or a rotating sensor add inertia to the system.
- In general, sensor should be in **solid state** (no moving parts) or **non-contact** (no physical contact between the sensing elements in relative motion) for reduced chances of mechanical failure and reliability. It is desired to reduce the number of auxiliary components such as slip rings to transfer the signal and power to the controller interface. This helps in minimizing overall complexity and size and also reduces potential failures.

2.3.2 Sensing and Measurement Attributes

- **Accuracy**: It is the maximum difference between the actual value and the measured value by the sensor. The actual value is the ground truth and is measured by a good primary standard. Accuracy indicates the closeness of agreement between the measured and the actual value of the measurand. It is typically expressed as a fraction of the reading (or full scale reading) or in absolute terms.

- **Sensitivity**: It is expressed as the ratio of change in output signal to a small change in the input signal. It can also be defined as the minimum input of a physical parameter that will create a detectable output change. Sensitivity error refers to a departure from the ideal slope of the characteristic curve (Figure 2-3). High sensitivity is desired for sensors.

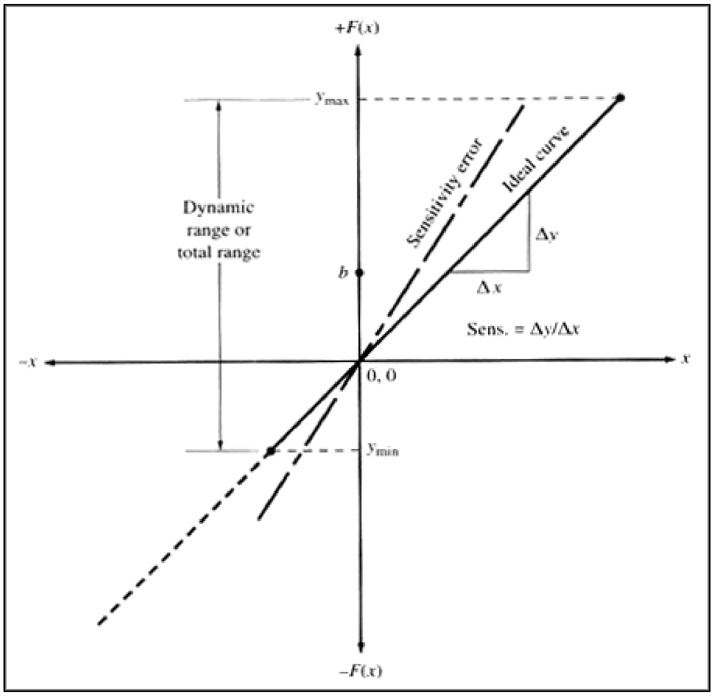


Figure 2-3: Ideal Curve and Sensitivity Error [J. J. Carr, Sensors and Circuits]

- **Resolution**: It is a smallest change in the input parameter that can be detected at the output signal. It is typically expressed as a fraction of the reading (or full scale reading) or in absolute terms. In general, high resolution is preferred for sensors.

- **Precision**: It is the degree of reproducibility or repeatability of a measurement. Precision is the closeness of agreement among independent sensor readings under the same conditions.
- **Measurement Range**: It refers to the maximum and minimum values of the parameter that can be measured using the sensor. The range of the sensor must match or exceed the expected variation in the measurand during the operation.
- **Response Time**: This refers to the time required for sensor output to reach within tolerance band of the new value of the measurand. Sensors require finite time to detect a change in the physical property. Similarly, decay time refers to the time after a step change in physical signal for sensor output to decay to its original value (Figure 2-4). Sensor bandwidth refers to frequencies that can be captured and presented in the output when measuring a varying signal.

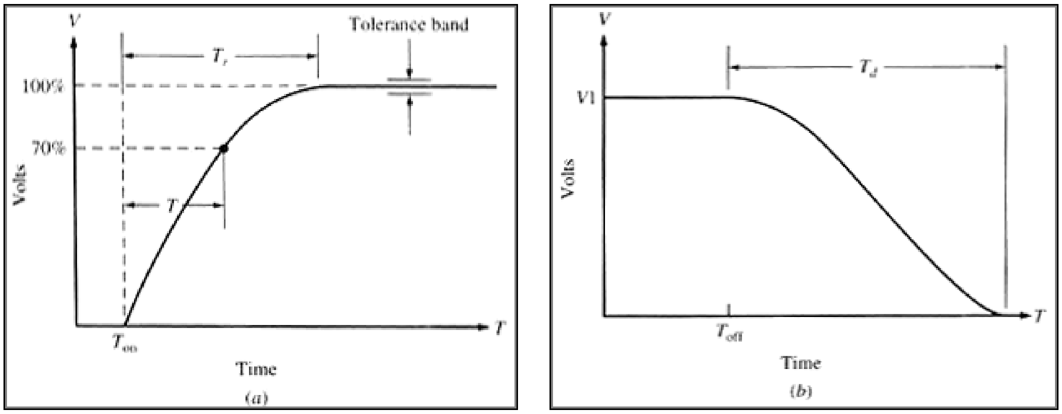


Figure 2-4: Response time, Rise-time and Decay-time [J. J. Carr, Sensors and Circuits]

- **Sampling Rate**:This is related to response time and bandwidth. It refers to how fast the data acquisition system can sample for new measurement data. A high sampling rate is desired in sensors for real-time/online monitoring and control.
- **Linearity**: It denotes extent to which the actual measured curve of the sensor deviates from the ideal curve. Figure 2-5 shows an exaggerated relationship between the ideal (or least square fit) line and the actual measured curve.
- **Hysteresis**: Sometimes output of the sensor is not just dependent upon the current measurand value but also on the past, i.e. how that value was achieved. It matters from which direction the change is made (lag). Approaching a fixed input value from a higher value will result in a different indication than approaching the same value from a lower value. Figure 2-5 shows typical hysteresis curve. Sensor should exhibit minimum hysteresis effect.

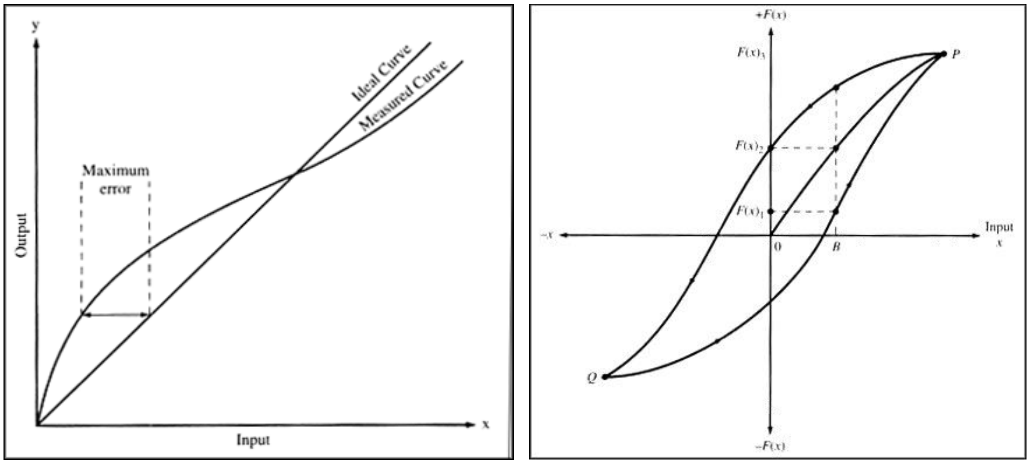


Figure 2-5: Linearity Error and Hysteresis Curve [J. Carr, Sensors and Circuits]

- Ideally, sensing should be self-energizing and should not need an excitation power supply (piezoelectric sensors). For non-active sensors, power consumption should be minimum to reduce heat generation. It is ideal in a multi-sensor integration process to have all or most of the sensors use a common power supply or the least possible number of supplies (typically ranging from 0 to 24 V).

2.3.3 Data Processing and Data Transmission Attributes

- **Embedded Processing**: Sensors are no longer simple transducers, they combine sensing, signal processing and communication in a single hardware package. Sensors with embedded processing capabilities and signal conditioning features are desired over the ones which dump raw data for the central controller to handle. Sensors should be capable of translating raw data into useful information. Rerogrammability in the sensor operation (range, sample rate etc.) gives additional flexibility in the application.
- **Built-in, Self-Test Feature**: A sensor should be able to detect its own working reliability. This reduces reliance upon an external test setup/algorithm (for example IMU calibration) and reduces repair cycle time. Additionally sensors are desired to have capabilities like compensation for cross-sensitivity, temperature compensation, auto-calibration etc.
- **Noise**: Sensors with higher signal to noise ratios are preferred. The signal can be amplified before noise comes in from other sources. In-built noise filtering circuits/algorithms are possible. The noise issue can be further reduced largely by proper cabling.

- **Communication Interface**: Sensors with multiple standard communication interfaces/protocols are desired. Automatic detection in a network (plug and play, hot swapping), signal amplification, reduced transmission power are some of the desired attributes.

2.4 PRACTICAL APPROACH FOR MULTI-SENSOR SYSTEM DEVELOPMENT

All of the above listed attributes are desired in sensors but when it comes to developing a multi-sensor environment for an existing commercial system, some of the most important factors in the selection of sensors are cost, maturity level and commercial availability of the sensors. For example a sensor in the prototype or research and development phase may exhibit excellent characteristics mentioned above but it may not have become a well-tested, commercial product yet or it may be very expensive. Hence it is imperative to consider the benefit to cost ratio while evaluating the sensor options. There is a trade-off between the sensing requirements and feasibility and benefits under available resources. Nonetheless it is worthwhile to consider all the sensors, including the ones still in the lab environment/prototype phase while developing a multi-sensor architecture for intelligent systems.

The idea is to list required sensing domains, four to six sensors in each domain and rank them based on the above mentioned attributes, including cost and maturity level. Weights can be given to each attribute based on the application to find the normalized ranking (for example lower power consumption may not be as important as ruggedness in an outdoor application). Normalized ranking is nothing but the weighted average of ranks. Now the selection decision can be made based on the normalized ranking of sensors in the sensing domain and the importance/necessity of the sensing domain. It is apparent that the selection process markedly differs from the design or analysis process. There are many solutions which satisfy the requirements to varying degrees and the goal is, similar to a constrained optimization problem, to select the solutions which best fit the requirements and provide best a benefit to cost ratio.

Once the optimum suite of sensors is selected, the next task is sensor integration. Integration refers to both, the physical placement of the sensors and the integration of the information coming from different sensors. Although the physical location of a sensor is more or less confined to the region where the phenomenon is being measured, clever placement of the sensor in the region can increase the sensor’s effectiveness, strength of output, reliability of the data and fast response to the actual changes in the measurand. For example, temperature reading at the railroad car bearing adaptor will be noticeably lower (20 to 30 degree Celsius) than the reading at the bearing cup due to convective cooling and contact resistance at the bearing-adapter interface (Figure 2-6). Moreover, the adapter temperature also lags behind the bearing cup surface temperature due to thermal resistance associated with longer heat transfer path [Kypuros et al., 2011]. This might be critical for real-time monitoring of bearings as the temperature rise and consequent bearing failure could occur within a period of a few seconds. Hence considered decisions should be made regarding the placement of the sensors. Simple simulations or FEA models can aid in finding the optimum location for sensing a phenomenon (Figure 2-6).

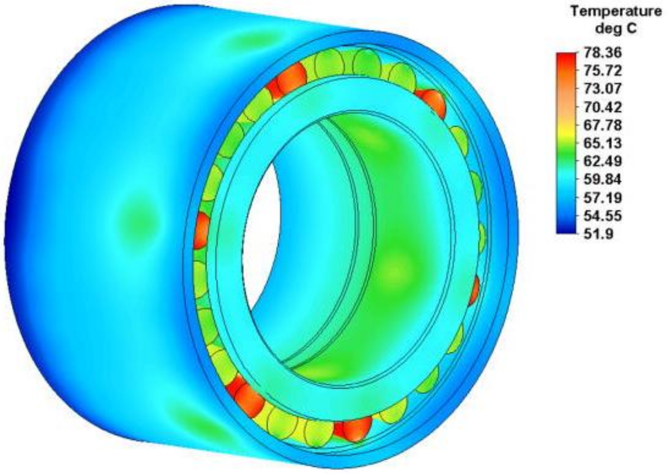


Figure 2-6: Thermal Model of a Railroad Bearing [Tarawneh, et al., 2012]

Physical integration also refers to connecting all the sensors to the controller. The idea is to use standardize interfaces and utilize common wires for multiple sensors to alleviate cabling complexity. A careful and systematic approach results in numerous benefits when the system is operational such as noise elimination, optimized data flow, and easy hardware debugging.

Once all the selected sensors are optimally placed and connected to the central controller (either directly or through local embedded processors/controllers using standard communication protocols), the next task is information integration. It refers to the use of data coming from multiple sources to achieve goals of intelligent control, condition based maintenance, and fault tolerance. Integration of multiple sensory data sources can increase the confidence in actual state information and ensure robustness. This requires resolution of conflicting data for the same measurand obtained from different sources. Fault tolerance requires inference of lost data from other available resources. Various methods exist in information and estimation theory (Kalman filter, particle filters, Bayes reasoning etc.) towards integrating data from multiple sensors and inferring the lost data. [Ashok, Krishnamoorthy and Tesar, 2010] provide guidelines for managing multiple sensors by forming a network of sensors and taking advantage of relational nature (analytical relationships) of the diverse measurands. Figure 2-7 shows two such possible networks for electro-mechanical actuators.

All the functionalities and algorithms have to be encapsulated into a single software framework which will be the brain of the intelligent system.

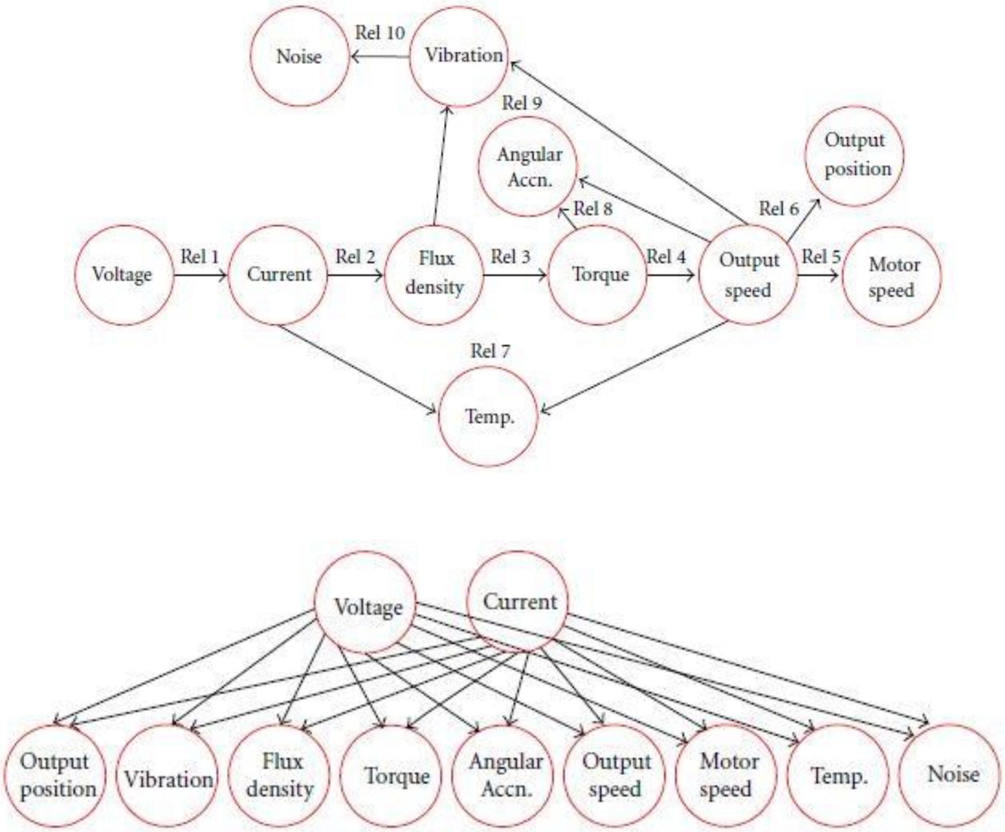


Figure 2-7: Possible sensor networks based on analytical relationships in electro-mechanical actuators [Ashok, Krishnamoorthy and Tesar, 2010]

2.5 EXAMPLES OF MULTI-SENSOR SYSTEMS

Development of a multi-sensor intelligent system is not a new field. A systematic approach for the design of instrumentation architecture and sensor data fusion concepts are presented which together enable the robust control of complex electromechanical systems, specifically addressing flexible space robots [Stieber et al., 1998]. Incorporation of multiple sensors in a complex system is evident in many fields, from nuclear reactors to air crafts. Although in many systems, real-time sensor data was not used in a manner to achieve direct intelligent control. It is only now, with the advent of enhanced computational capabilities and availability of low cost sensing, it has become feasible to add more and more sensors in a system to improve performance and safety. Recent developments in the field of mobile robots include suite of sensors such as inertial measurement unit, range finder, cameras, sonar etc. for autonomous navigation. Automobile industry is equipping their modern cars with multiple sensors to improve ride quality and safety.

The goal is to expand this development to all the existing systems, including at the component level to get increased awareness, intelligent control and change the way systems are conventionally operated.

A multi-Sensor architecture for electro-mechanical actuators has been developed [Krishnamoorthy and Tesar, 2005]. Ten sensors were suggested to be embedded inside the actuator. These include angular position, velocity and acceleration sensors, torque sensor, temperature sensor, microphone, vibration sensor, magnetic flux density sensor, and current and voltage sensors. Inclusion of these sensors will enable intelligent control of the actuator based on operating conditions and user set criteria. It will also allow condition based monitoring of the actuators for incipient faults. Actuator being building block of all the moving systems, a multi-sensor architecture in actuator will enhance overall system performance.

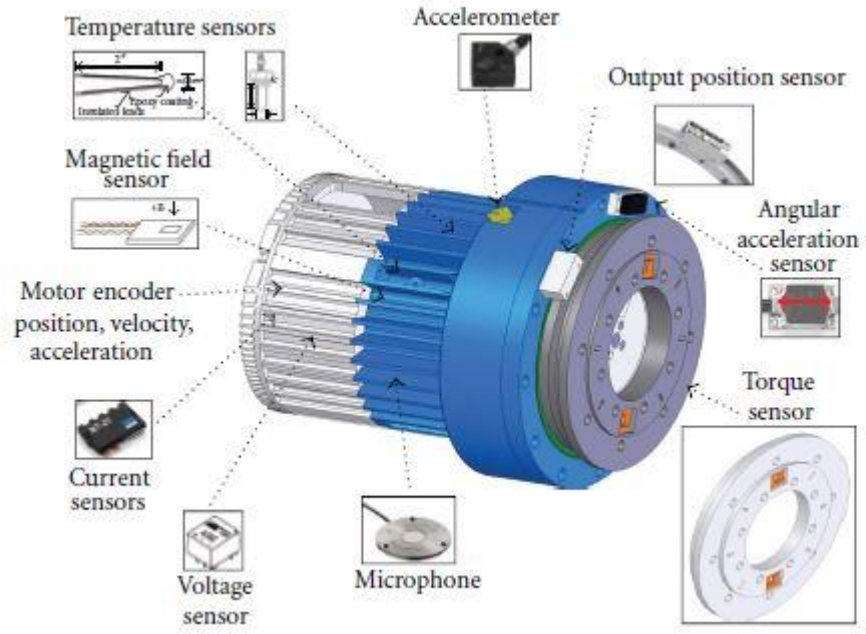


Figure 2-8: Multi-sensor architecture electro-mechanical actuators [Krishnamoorthy and Tesar, 2005]

McFarland [McFarland and Tesar, 2010] evaluated multi-Sensor environment for monitoring Soldier performance in real-time. The study assessed ten potential physiological indicators (same as sensors), termed biomarkers that correlate with human task performance condition (response to select set of stressors). These biomarkers include heartbeat, muscle activity, blood pressure, facial stresses, pupillometry, eye movements, skin response, temperature, and oxygen saturation. The goal is to monitor Soldier performance in real-time by means of visual 3D performance maps supported by Bayesian network model of soldier performance.

The benefits of a multi-sensor environment are numerous. Cost, maturity of the technology and commercial availability are important factors in the selection of sensors for a particular application. The next two chapters discuss multi-sensor environment in the purview of railroad freight trains (railroad cars) and vehicle systems. Sensing requirements are evaluated and suitable sensor technology, current state of the art and commercial sensor options are suggested for both the systems.

Chapter 3: Multi-Sensor System for Railroad Cars

Freight railroads play an important role in a country's economy. They move a large share of the nation's freight, including export and imports from one place of the country to another. Freight trains are also the primary mode of transportation for shipments of coal and oil, fueling the country's industrial growth. The United States' freight rail network is one of the most dynamic freight systems in the world, accounting for approximately 40% of the total fright moves by ton-miles (the weight times length the freight travels) and 16 percent by tons (the weight of freight moved) in the country [National Rail Plan Progress report, 2010]. To respond to such a high demand, the U.S. Class I railroads (railroads with 2011 operating revenue of $433.2 million or more) operate over 360,000 freight cars and 24,500 locomotives, generating about 70 billion dollars annual revenue in the operation [Association of American Railroads, 2013].

As a mechanical system trains are remarkably complex, having many highly non-linear coupled parameters. If one goes into detail, each car truck requires as many as 41 parameters to provide a highly non-linear description of its actual physical response to a wide variety of track-based inputs (Coulomb friction, track width/centerline variation, track tilt, vertical motion etc.) [Sankar, 1987]. The tracks vary a great deal in elevation (± 3 inches), in straightness (± 6 inches), in curvature (up to 8° turns), in surface wear, in temperature effects etc. Moreover, each car is different in shape, height, has its own load configuration and distribution of supports (wheel/axle placements), open or closed cover, etc.

3.1 IMPORTANCE OF MULTI-SENSOR ARCHITECTURE IN RAILROAD

In the past, limited resources were available to monitor the train's condition in real-time. This was the case mainly due to unavailability or immaturity of the sensing technologies at the time. Defect detectors that are wayside sensors are installed along the side of the tracks to detect axle or bearing problems when a train passes by. But these wayside sensors can only give intermittent readings. These expensive detectors (≈ $50,000) even when installed every 30 miles along the track are only capable of providing measurements every 30 minutes for a train travelling at 60 mph. It can take less than five minutes for a journal bearing on the freight car to heat up and fail. Additionally wayside sensors have very small amount of time to assess and identify the defects. Lack of confidence in the measurements results in many false alarms. Any alarm requires the train to be stopped and manual assessment of the components by the train crew. An unnecessary stoppage due to false alarms causes significant train network management problems and costs thousands of dollars to the operator.

As the railroad business is expanding, it becomes increasingly essential to monitor and gather data in real-time to make informed decisions to improve safety and efficiency in train operation. Real-time data for active components in the locomotive such as engine, generator motors already exist to some extent. It is now proposed to develop a full sensor suite made of low cost, small and rugged sensors to deploy on the railroad cars which will give continuous information about the operational state of the car components. The train crew will have real-time operational data displayed graphically on the train computer and alarms can be triggered to warn against potential failures during operation.

In this chapter, wayside sensors and other currently used technologies are reviewed. Limitations of the current methods are discussed and multiple onboard sensors are proposed for real-time monitoring of freight trains. Techniques for increasing confidence and reducing false alarms using multiple complimentary sensors are also described.

3.2 RAILROAD WAYSIDE SENSING TECHNOLOGIES

Wayside sensors are integrated with the track or installed by the side of the track to monitor train components and detect possible defects. Wayside sensing systems typically include auxiliary sensors such as AEI tag reader, wheel detectors, train speed sensors, etc. along with the primary sensor for the system to correlate data with axle count or car number. Signals from these sensors are routed through a junction box to a trackside bungalow which houses power, signal conditioning units, data processing and data storage hardware and has the communication capabilities to transmit the data to operator's traffic control and monitoring facility.

Way-side sensors have been used to gather variety of information about the passing freight trains. These include axle-wheel bearing conditions, wheel profile, freight car loading conditions, car stability, brake pad condition, etc. These way-side sensors have helped avoid many railroad accidents and reduced frequency of manual visual inspections required by the train crew and track-side workers. Some of the way-side sensing technologies are discussed below.

3.2.1 Axle Load Sensor – Weigh-In-Motion

Freight train axle/wheel load sensing is done using Weigh-In-Motion system. Weigh-in-Motion allows measurement of the load and its distribution in the car while the train is moving, thus increasing the speed and efficiency of the operation. Various principles are used in rail mounted sensors for load measurement, for example strain gauge (measuring the strain in the hub of the rail), fiber optical sensors (change in intensity of the light caused by rail bending), load cells (strain change), laser based system which measure displacement in the rail, etc. Weigh-in-motion systems can be installed on the main lines to measure weight distribution of an entire train consist (coupled-in-motion weighing) or in the yards for individual cars at lower speed (uncoupled-in-motion weighing). These systems detect overloaded cars, uneven load conditions of cars, damaged wheels, flat spots etc. to protect rail infrastructure and prevent derailments and other catastrophic failures due to unsafe loading.

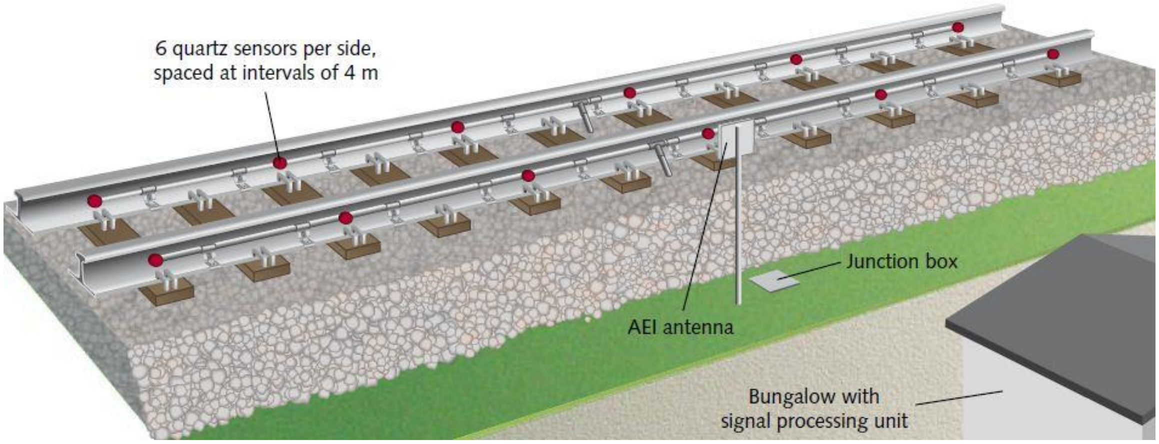


Figure 3-1: Kistler Weigh-In-Motion (WIM) System [www.kistler.com]

The Kistler "Overload and Impact Detector" WIM system uses quartz sensors mounted on both the rails for weight determination (individual wheel and axle-loads, and gross car weight) and imbalance detection (front/back and left/right). Sensor signals are conditioned and processed in a way side bungalow and WIM data is stored on a local hard-drive or transmitted to operator's remote facility.

3.2.2 Wheel Impact Load Detector

Wheel Impact Load Detector (WILD) systems are used to measure impact of the wheel on rails and hence identify defects such as flat spots on the wheel surface. Wheel flats are caused by locked bearing, unwanted slipping on the rail without turning (due to fully unreleased brakes while moving) or overloaded axles and defects in the truck's suspension. Wheel flats can cause severe problems such as dynamic instability of wagons, overheated wheels, damage to rails and even train derailments. Hence it is essential to detect wheel defects at an early stage for timely repair and maintenance.

Figure 3-2: Wheel Surface Defects and Flat Spot [www.tsb.gc.ca]

The Wheel Impact Load Detector (WILD) system consists of a series of rail mounted (micro-welded) strain gauges. It measures impact forces caused by damaged wheels. Strain gauges span between several ties to measure as much of the wheel surface as possible (the wheel can rotate 3-5 times in the sensing length). As a wheel rolls over the site, rail deflects between the ties and the strain gage estimate the force. The highest vertical force is the peak impact. Nominal forces correspond to the normal/expected load on the axle. Hence WILD can also be used to identify overloads or imbalanced loads.

Figure 3-3: Wheel Impact Load Detector (WILD) System [www.lbfoster-salientsystems.com]

Two factors affecting the impact measurements are weight of the cars and speed. Wheel impact is lower for a slower speed train. Hence the WILD system can be complemented by wheel sensors and AEI reader to correlate measured data with train speed and car load (empty vs. loaded). Impact measurement is possible for trains moving from 30 to 180 mph. Way-side bungalow houses signal processing hardware which analyzes data and isolates wheel defects. Multiple thresholds on acceptable impact forces can be set for warning alarms and real-time information is sent to an operator's remote monitoring facility.

3.2.3 Hot Box and Hot Wheel Detector

Hot box and hot wheel detectors are temperature monitoring devices installed along the tracks on a special sleeper. They monitor axle-wheel junction, bearing and brake temperature to indicate any possible overheating. Overheating occurs when the bearing lubrication runs out or due to defects in the bearings. If the problems are not detected early enough, it can cause fire or fracture in the axle which can lead to major derailment of the train. Hot box and hot wheel detectors are based on the principle of pyrometer (thermal radiation) or use infrared/laser signals to find the temperature of the object they are pointing to.

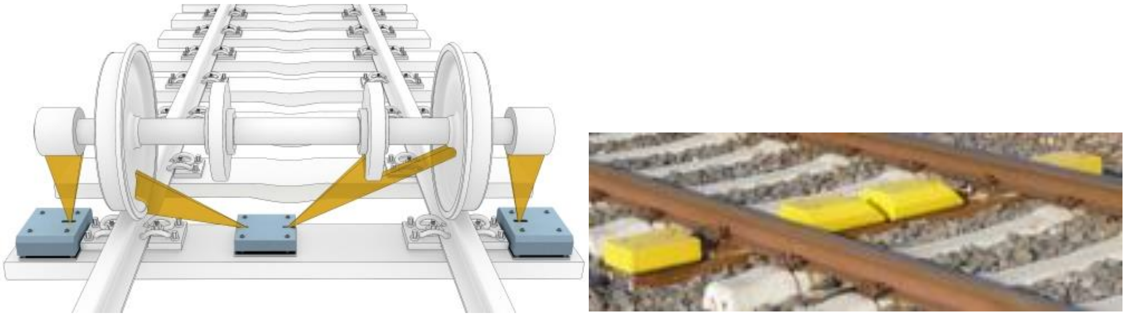


Figure 3-4: Hot Wheel and Hot Box Detectors [www.mermecgrou.com] and [www.sst.ag]

MERMEC group’s PEAGASUS – The hot box/hot wheel detector system uses infrared radiation for temperature measurements of passing rolling stock. The system consists of detection units which are located inside a special sleeper and a processing unit located at the trackside which collects the values measured by the detectors and transmits this data to the traffic control and monitoring section [www.mermecgrou.com]. The degree of overhearing is estimated and an alarm can be set for the heated hot box. The measurements can be carried out for trains travelling as fast as 200 mph.

3.2.4 Brake Pads Wear

The way side brake pads wear measurement system is used to assess the condition of brake pads and wheel brake interaction. It measures dimensions of the brake pads (thickness), brake disk rotor width, brake temperature to identify potential asymmetric wear, brake shoe wear, taper wear, missing hardware etc. Interaction between wheel and brakes is the most important factor in the safety and quality of rail transport. Brake pad scanning systems automate the brake inspection process and provide immediate feedback. The system when integrated with other wayside detectors including wheel profile, wheel impact and hot wheel detection systems can provide valuable information about rolling stock components and can identify any locking up or malfunctioning of brake system.

The BrakeScan system from KLD Labs utilizes a strobe light source to illuminate each wheel and a high resolution machine vision technology (CCD cameras) to capture brake profile images. It automatically detects feature points and performs dimensional measurements on the brake pads in real time. It compares brake condition with set allowed thresholds and raises an alarm if unusual conditions are detected. The system provides base information for an appropriate maintenance plan, keeping brake pads within quality standards. But some of these systems are capable of measurements with trains running only up to 12 mph [www.mermecgrou.com]

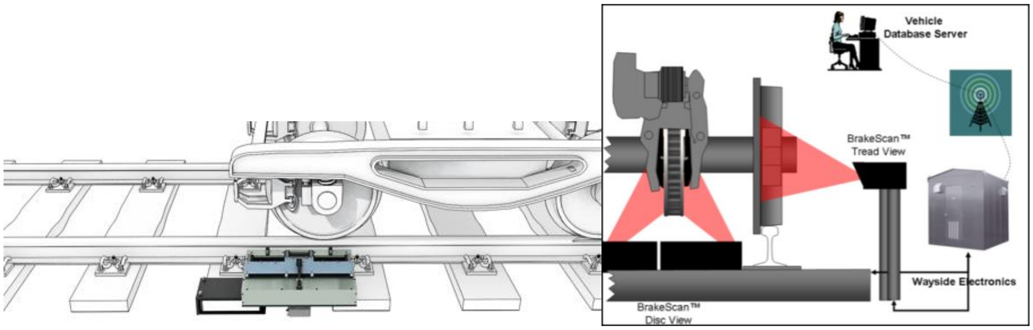


Figure 3-5: Brake Pad Wear Measurement [www.mermecgrou.com] and BrakeScan-Brake inspection system [www.kldlabs.com]

3.2.5 Acoustic Bearing Detectors

Acoustic bearing detectors are used to detect bearing defects using acoustic signals. These bearing detectors use an array of microphones for capturing acoustic signals when a train passes by. Detectors also have embedded signal processing units for signal conditioning, filtering of data and getting meaningful information from the raw data.

In the past two decades, considerable research has been done to evaluate the possibility of using acoustic signatures from the bearing for identification of bearing defects. The Federal Railroad Administration has conducted multiple field tests to record and evaluate the acoustic data from healthy and defective bearings on the train using an array of microphones installed by the side of the track [DOT/FRA/ORD-00/06.II, FRA Report, 2003]. Neural pattern identification techniques are proposed with the fast Fourier transform (FFT), the continuous wavelet transform (CWT), the discrete wavelet transform (DWT) features of audible acoustic signals to detect bearing defects [Choe et al., 1997].

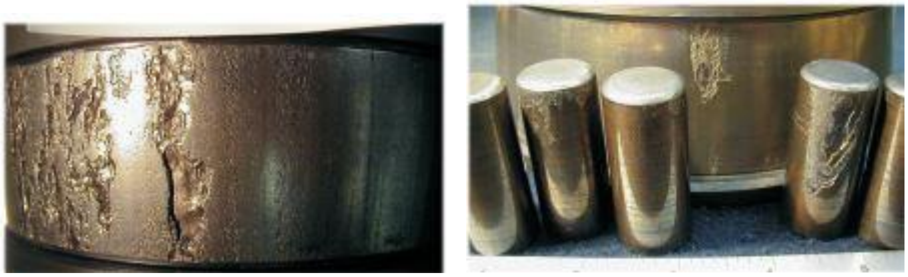


Figure 3-6: Bearing cone and roller spalls[www.aar.com]

The critical bearing defects are spun cone and damaged rollers. Bearing defects cause peaks in the acoustic data at regular intervals. In the spectral analysis of acoustic signals, one of the major frequency components is related to the rotational rate of the bearing (4.5 Hz at 30 mph). The next higher frequency peak in spectral analysis comes directly from the cup defect repetition rate. It is concluded that acoustic data can be reliably used to identify defective bearings. The acoustic systems can supplement the hot box and hot wheel detectors for identifying the bearing defects.

Figure 3-7: Trackside Acoustic Detection SystemTADS® [Transportation Technology Center, Inc.]

The Trackside Acoustic Detection System TADS® by Transportation Technology Center, Inc. can be used to identify bearing flaws in early stages to reduce burn-offs and derailments. It is capable of detecting cup, cone and roller defects (spalling, brinelling, water-etch) and loose cones on freight car bearings. Bearing defect information is AEI integrated and can be transmitted to a remote monitoring location.

Many other way-side detectors such as Dragging equipment detectors, High car or shifted load detector, Structure gauge and loading gauge, Wide-load detectors etc. exist and are already in place. Using these wayside sensors, railroad operators have reduced bearing related derailments by 75% [Murphy, 2012]. But a main disadvantage of the way-side detectors is that the components are monitored or defects are detected only when a train passes in front of them. These expensive (≈ $50,000) sensors are installed every 20 miles along the track and data is sent via fiber-optic cables that run alongside tracks to a remote monitoring site. Data analysis is done and the train crew is warned to slow down or stop the train if the measurements indicate possibility of defects. Thus the information about the train components goes from the way-side detector site to the remote monitoring location to the train-crew. This time delay can be crucial as some of the failures can lead to catastrophic effects within minutes of detection. Moreover, only a short amount of time is available for the measurement of components using wayside sensors when the trains are travelling more than 60 mph. This results in many false alarms which can cause unnecessary stoppage of a train. A false alarm not only affects a single train but also the entire train network has to be slowed down which costs thousands of dollars to the operator. Infrared temperature sensors used in way-side hot box detector systems can only identify bearing defects in a later stage of failure when temperature effects are apparent. The earliest failure signs are obtained in vibration analysis and later in the acoustic (audible) signals coming from the bearing. Hence there is an immediate need to get more real-time data directly from the sensors deployed on the cars. This data can be presented to the train engineer to make informed decisions about the operational condition of the components in real time. This will enable scheduling for timely maintenance of the degrading components when a train is at the yard, thus reducing downtimes during actual operation.

3.3 FREIGHT TRAIN ONBOARD SENSORS

Sensor technologies have improved significantly over the past decade. It is now possible to utilize and manage multiple sensors to support intelligent decision making in the system. For the railroad business, it is becoming vital to continuously monitor and gather real-time data about the freight train’s operational condition to make expeditious and informed decisions. This will require development of a suite of low cost, tiny, rugged sensors to deploy on the railroad cars and truck chassis. These onboard sensors can give continuous information about the state of the car and its components to the train crew. Such a multi-sensor system will impart high intelligence to the railroad system and its integration will result in increased efficiency, performance, and safety in the overall railroad operation.

Efforts have already begun towards onboard sensing and real-time monitoring of freight trains. The Transportation Research Board's IDEA (Innovations Deserving Exploratory Analysis) program has triggered many projects in the area of onboard, real-time sensing of freight car components. The Federal Railroad Administration (FRA) also conducts and facilitates research and development activities in the field of onboard monitoring and control of freight trains for improving transportation safety.

The most pressing requirement in the railroad industry is for continuous monitoring of bearings for increasing safety and efficiency (predictive maintenance) in the operation. The earliest stage to detect bearing failures is provided by vibration analysis. Zhang [Zhang, 2011] recommends asserts using accelerometers on the bearing adapter to identify defective bearings. Spectral analysis of vibration signals from defective bearings on rotating machinery is a mature technology, used in many industries. This technology can be successfully used for railroad bearings to isolate vibration signals originating due to defects using low-cost accelerometers. Field tests show peaks in the vibration amplitude for defective bearings consistently occurring at a frequency proportional to speed of the train (for ex. 70 Hz at 40 mph). Power spectral analysis of vibration signals clearly distinguishes between the good and the defective bearing. At a later stage of a defect, audible noise and temperature effects are also apparent. A correlation between the vibration signatures of defective bearings and the bearing surface temperature rise is observed using data collected from an on-track field test and laboratory experiments [Gonzalez, 2010]. Railroad bearings in the test and experiments were equipped with temperature sensors and vibration sensors attached at multiple locations. Choe [Choe et al., 1997] proposed and carried out neural pattern identification techniques on features extracted from audible acoustic signals to detect bearing defects.

Tabacchi [Tabacchi et al., 1990] developed a prototype of a “Smart Bolt” with an embedded thermal temperature sensor at the Carnegie Mellon Research Institute. The “Smart Bolt” with thermal sensor and transmitter contained in the body replaces a standard bearing end cap bolt at each end of an axle to provide real-time continuous monitoring of bearing temperature. IONX LLC, a subsidiary of Amsted Rail has developed low power wireless temperature sensors to be fitted on the bearing adapter surface. These wireless sensor nodes (WSN), are currently being used on ten railroad cars (part of an Australian fleet) to provide continuous monitoring of bearing temperatures as well as current ambient temperature. Kypuros [Kypuros et al., 2011] has devised correlation methods to estimate bearing cup temperature from the adapter surface temperature recorded using these WSNs. Many other efforts are in progress for continuous monitoring of railroad bearings.

The Federal Railroad Administration evaluated an onboard brake piston travel sensor system for continuous monitoring of air brakes [FRA Research Result, 2009]. Piezoelectric, magnetic (Hall effect), fiber optic and proximity sensors were evaluated to measure air brake piston stroke. The selected onboard proximity sensor measures brake piston travel and relays information to the locomotive engineer in real-time to monitor/assess brake performance (amid brake shoe wear, presence of debris, etc.). This research demonstrated cost-effectiveness and safety benefits of continuous remote monitoring of brake piston travel.

In other research [DOT/FRA/ORD – 10-04], the Federal Railroad Administration instrumented a tank car with various onboard sensors to understand the operational environment and forces exerted on the tank car. Sensors included accelerometers at multiple positions, vertical load adapters, strain gages, instrumented couplers, instrumented wheel sets and pressure transducers. Data from these sensors were synchronized with the track geometry data measured by a track inspection car to evaluate the track induced effects. Strain bridges and shear gauges were used to measure longitudinal and vertical forces on the coupler. Strain gauges also measured bolster forces. A tri-axial accelerometer mounted on the car body measures car acceleration. Vertical accelerometers were also mounted on the tank car stub sill and bearing adapters. Vertical load adapters were modified bearing adapters used to measure wheel forces using strain gauges. A pressure transducer was used to measure brake cylinder pressure. In addition, each wheel and axle of one truck was instrumented with strain gauges in several configurations to measure the vertical, lateral, and longitudinal forces at the wheel/rail interface. Force data from the coupler, bolster and the wheels matched (as expected) with braking/acceleration events, switches on the track, dips and bumps on rail etc. All these sensors were installed only for a test run and to record data for normal operating conditions.

Onboard sensors such as GPS, yaw rate and speed sensors can be used to estimate and classify railroad geometry [Trehag and Handel, 2010]. Yaw rate and speed data sampled at 300 Hz were integrated with GPS data sampled at 1 Hz using an Extended Kalman Filter to find smoothed track curvature and its rate of change. Earlier Riewe [Riewe, 1996] used an Inertial Measurement Unit (Low-cost MEMS accelerometers) on the locomotive for navigation and to detect track switching. Low cost MEMS gyroscopes can help in real-time track detection in railway sidings and to reliably know the path the train has taken in a switch [Broquetas et al., 2012].

The Federal Railroad Administration facilitated the Onboard Monitoring and Control System (OMBCS) project to demonstrate an integrated package of sensors and actuators for monitoring and controlling mechanical components on freight trains. The OMBCS includes sensors to monitor bearings, wheels, brakes and trucks and actuators for brakes, angle cocks etc. to improve safety and efficiency in freight train operations. Science Applications International Corporation (SAIC) has developed an open system network architecture based on CAN technology (CAN bus network) to provide integration and control of the advanced components in OBMCS [Edwards, 2005]. The power for the sensors and CAN system was generated from Timken generator bearing.

Many other researchers are also developing new sensors for onboard condition monitoring. The idea here is to unify all the approaches, extract important results from the previous and the currently progressing work to identify critical sensing domains and approaches for real-time onboard freight car monitoring. The goal is to present to a railroad operator all the essential and supplementary sensing requirements and a list of sensors in each sensing domain to deploy on freight cars for improving safety and performance in the railroad operation. These sensors need to be low-cost and commercially available to be feasible to deploy on all the railroad cars. Some low-cost sensors may require an external rugged casing to work in the railroad environment for many years. Moreover, more than one sensor can be used to estimate the same physical measurand. This redundancy improves confidence in the sensor data and provides fault tolerance in the system.

The following sensors are suggested for the deployment on railroad cars. Sensors are grouped by their location on the freight car.

Railcar body	Inertial Sensors – Inertial Measurement Unit • Accelerometers • Gyroscope (Yaw, pitch and roll rate) • Tilt Sensing Load Sensor Proximity Sensor (Door lock) Temperature Sensor Pressure Sensor for tanker valve Toxic gas leak sensor Humidity sensors for goods
Car Chassis and Couplers	Vibration sensors Load sensor (strain gauges) • Rail impact sensor • Coupler forces Temperature sensor Vision sensor
Axle, Wheel and Bearings	Vibration sensors/accelerometers Microphone (bearing and wheel defects) Temperature sensor (bearing defects) Shock/impact sensor Proximity sensor (brake piston travel) Angular velocity sensor (wheel Slip)

The next section discusses some important sensing domains and their proposed use in railroad freight train operation. Low cost commercially available sensors are suggested in each sensing domain for their potential use on railroad cars. Sensor characteristics are described in a standard one page format listing their hardware, sensing, data processing and data transmission attributes to give a broad view of the current state of technology to the railroad operators.

3.3.1 Accelerometer

Accelerometers and vibration sensors can be mounted at multiple locations on a railroad car. Amplitude and frequency range are two of the most important parameters in selection of an appropriate accelerometer for a given application. It is desired that the operating range spans the accelerometer’s measurement range to get maximum sensitivity.

- A three axis accelerometer on the car body can capture the response of the freight car as a rigid body to the locomotive accelerations and decelerations, braking and track curvatures. This accelerometer can be operating at ±2g range to sense low frequency (0-20 Hz) oscillations such as lateral hunting (typically less than 3 Hz), and oscillations due to track irregularities and train slacking. An accelerometer on the car body can also complement an onboard gyroscope to measure tilt or inclination of the freight car.
- A mid-range ±10g accelerometer is suitable for measuring the vibrations of the truck bogie and unsprung mass (0-500 Hz excitation).
- An accelerometer on the bearing adapter or near wheel/axle should be able measure high frequency vertical vibrations (0-1500 Hz) and impact forces (± 300g) coming from wheel and rail interaction. This accelerometer can monitor for wheel flats, wheel corrugation, bearing defects, irregularities in the track components etc.

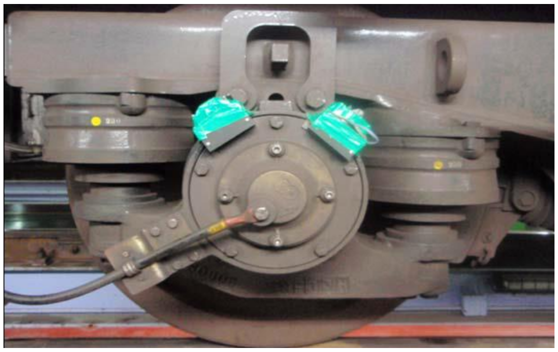


Figure 3-8: Accelerometers - ADXL278 (± 50g) on the bearing adapter [Kim et al., 2011]

Conceptually an accelerometer behaves as a damped mass spring system. The mass is displaced relative to the accelerometer mounting which causes deflection in the spring element. Piezoelectric, piezoresistive or capacitive elements convert mechanical motion into an electrical signal. Modern accelerometers are low cost sensors based on MEMS technology. These accelerometers provide user selectable measuring range and bandwidth (user set filter components) with very little power consumption. They are small size (a few millimeters) and can be integrated on a circuit board with other sensors, a micro-processor and data transmission circuit.

Table 3-1 lists two choices for low cost accelerometers (high g and low g) to deploy on freight cars. A rugged casing is required for their operation in harsh railroad environment.

Table 3-1: Commercial choices for accelerometers and vibration sensors

Accelerometer Location	Device and Manufacturer	No. Of axis	Range	Power Requirements	Cost per unit
Low g Car body, above bolster	**MMA8452Q Freescale Semiconductor**	3	±2g, 4g, 8g	1.95-3.6V, 165µA	$0.68 (10000 Pcs)
	ADXL 345 Analog Devices	3	±2, 4, 8, 16g	2.0-3.6V, 40-145µA	$3.54 (100 Pcs)
Medium, High g Axle, bearing	**ADXL193 Analog Devices**	1	±120g, ±250g	5V, 1.5 mA	$6.68 (1000 Pcs)
	MMA81XXEG Freescale Semiconductor	1	±150g, ±250g	6.3 -30 V	$6.29 (1000 Pcs)

Low g Accelerometer

Producer/Product: Freescale Semiconductor (MMA8452Q)

Measurands:

- 3 – axis acceleration

Hardware Attributes:

- Industry standard, proven design
- Small and thin: 3mm x 3mm x 1 mm, QFN 16 package
- RoHS compliant
- Operating temperature: -40°C to 85°C

Sensing Attributes:

- Selectable measuring range ±2g, 4g, 8g, 400 Hz roll-off frequency
- 12 bit and 8 bit digital output
- 1.95V to 3.6V supply voltage
- Free-fall detection, Pulse detection, Transient detection

Data Processing Attributes:

- Self-test
- 2 independent programmable interrupt generators for free-fall and motion detection
- Activity/inactivity monitoring
- High-Pass Filter Data available real-time

Data Transmission Attributes:

- I2C digital output. Output Data Rates (ODR) from 1.56 Hz to 800 Hz
- 99 µg/ √ Hz noise

Cost: $0.68 (10000 Pcs)
http://www.freescale.com/files/sensors/doc/data_sheet/MMA8452Q.pdf

Low g Accelerometer

Producer/Product: Analog Devices (ADXL345)

Measurands:

- 3 – axis acceleration with high resolution (13 –bit) measurement

Hardware Attributes:

- Industry standard, proven design
- Small and thin: 3mm x 5mm x 1 mm, 14 lead, plastic package
- 10,000g shock retrieval
- Pb free/RoHS compliant
- Operating temperature: -55°C to 115°C

Sensing Attributes:

- Selectable measuring range ±2, 4, 8, 16g, bandwidth 400 Hz roll off frequency
- User-selectable resolution from 10 to 13 bits
- 2.0 to 3.6V power supply. Ultralow power consumption: 40 µA in measurement mode and 0.1 µA in standby mode at V_S = 2.5 V

Data Processing Attributes:

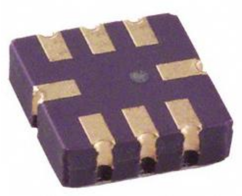
- Embedded, patent pending FIFO technology minimizes host processor load
- Activity/inactivity monitoring

Data Transmission Attributes:

- SPI (3 and 4wire) and I2C digital interfaces

Cost: $3.54 (100 Pcs)
http://www.analog.com/en/mems-sensors/mems-inertial-sensors/adxl345/products/product.html

High g Accelerometer



Producer/Product: Analog Devices (ADXL 193)

Measurands:

- Single axis high g acceleration for shock and vibration

Hardware Attributes:

- Industry standard, proven design
- Small and thin: 5mm x 5mm x 2 mm, 8 terminal LCC package
- 4000 g shock rating
- Pb free/RoHS compliant
- Operating temperature: -40°C to 125°C

Sensing Attributes:

- Measuring range – two options available with ±120g and ±250g, bandwidth 400 Hz roll off frequency
- High sensitivity – 8 mV/g for 250g model
- 5V at 1.5 mA power

Data Processing Attributes:

- Full differential sensor and circuitry for high resistance to EMI/RFI

Data Transmission Attributes:

- Analog

Cost: $6.68 (1000 Pcs)
http://www.analog.com/en/mems-sensors/mems-inertial-sensors/adxl193/products/product.html

High g Accelerometer

Producer/Product: Freescale Semiconductor (MMA81XXEG)

Measurands:

- Single axis (Z) high g acceleration

Hardware Attributes:

- Industry standard, proven design
- Small and thin: 7.5mm x 10.3mm x 3.5 mm, SOIC 16 package
- RoHS compliant
- Operating temperature: -40°C to 125°C

Sensing Attributes:

- Range: ±40g, 150g, 250g options available
- 400 Hz roll-off frequency
- 6.3V to 30V supply voltage

Data Processing Attributes:

- Self-test
- On-chip voltage regulator
- Incorporates digital signal processing for filtering and data formatting

Data Transmission Attributes:

- 10-bit digital data output from 8 to 10 bit DSI output
- DSI 2.0 compatible

Cost: $6.29 (1000 Pcs)
http://www.freescale.com/files/sensors/doc/data_sheet/MMA81XXEG.pdf

3.3.2 Gyroscope

A gyroscope measures rate of angular rotation (i.e. angular velocity). A gyroscope on the freight car can provide yaw, pitch and roll rate of the car body to monitor dynamic stability of the car and ensure safety of cargo. The angular velocity data can be integrated to get the angular position which can give a measure of tilt or inclination of the car. The integration process can induce errors (dead reckoning) in the angle estimation but it can be easily resolved using an accelerometer (sensing direction of gravity) or a magnetometer (sensing earth's magnetic field). Gyroscope yaw rate measurements can also be used to identify the path the train has taken in a track switch [Broquetas et al., 2012]. GPS is not reliable for safe dispatching and switching of trains as the GPS information is not accurate enough to know the location of the train between two parallel tracks. Location sensors are used on the tracks for this purpose but they do not give real time information about trains speed and acceleration. Thus an onboard gyroscope can be useful in augmenting the GPS data for accurate position awareness of the train.

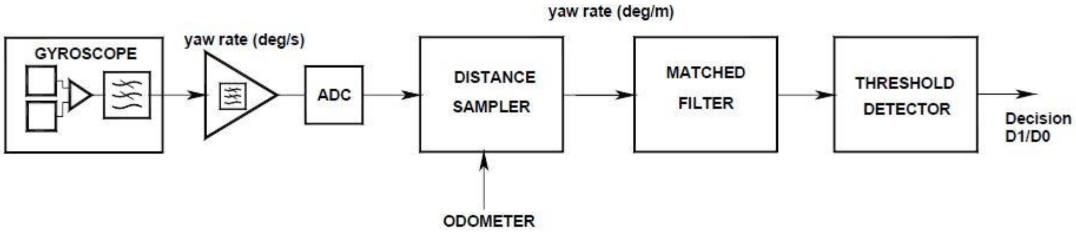


Figure 3-9: Track detection in railway siding using onboard gyroscope [Broquetas et al., 2012]

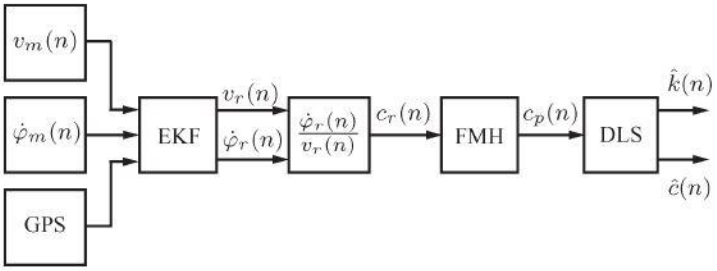


Figure 3-10: Gyroscope (300 Hz) augmented GPS (1 Hz) for onboard railroad curvature estimation and classification [Trehag, 2010]

Modern day gyroscopes are tiny low cost sensors based on a vibrating structure manufactured with MEMS technology. Similar to MEMS accelerometers, these are small (few millimeters) packaged like integrated circuits and provide an analog or digital output. They can be integrated with accelerometers and other sensors on a circuit board.

Pitch & bounce, yaw & sway, twist & roll, lateral hunting motion are all less than 4 Hz (1440 °/s) and suitable to measure using MEMS microphones. Robert Bosch GmbH, InvenSense, STMicroelectronics, Analog Devices are some of the major manufacturers of MEMS based gyroscopes. Two suitable low cost gyroscopes are given in the Table 3-2. A rugged casing is required to use them on railroad cars.

Table 3-2: Commercial choices for gyroscope sensors

Device and Manufacturer	No. Of axis	Range	Power Requirements	Cost per unit
L3G4200D STMicroelectronics	3	Selectable ±250°/s to ±2000°/s	2.4-3.6V, 6.1mA	$7.30 (cheaper in quantity)
IDG500 InvenSense	2 (x/y)	500°/s (high speed) 110°/s (high precision)	3V at 7mA	<$6.00 (in quantity)

Gyroscope

Producer/Product: STMicroelectronics (L3G4200D)

Measurands:

- 3-axis digital output gyroscope

Hardware Attributes:

- Industry standard, proven design
- Small and thin: 4mm x4mm x1.1mm LGA-16
- RoHS compliant
- Operating temperature: -40°C to 85°C

Sensing Attributes:

- MEMS motion sensor: Ultra-stable three axis digital output gyroscope
- Embedded temperature sensor
- Selectable ±250°/s, ±500°/s or ±2000°/s range
- 16 bit-rate value data output, 8-bit temperature data output
- Wide supply voltage: 2.4 V to 3.6 V

Data Processing Attributes:

- Embedded power-down and sleep mode
- Integrated low- and high-pass filters with user-selectable bandwidth

Data Transmission Attributes:

- I^2C/SPI digital output interface

Cost: $7.30

http://www.st.com/web/catalog/sense_power/FM89/SC1288/PF250373

Gyroscope

Producer/Product: InvenSense (IDG series)
Measurands:

- Integrated dual axis gyroscope. Angular velocity in 2 axis, Temperature sensor

Hardware Attributes:

- Industry standard, proven design, 10,000g shock tolerance
- Small and thin: 4mm x5mm x1.2mm QFN package
- Hermetically sealed for temp and humidity resistance
- RoHS compliant
- Operating temperature: -20°C to 85°C

Sensing Attributes:

- Integrated X- and Y- axis gyros on a single chip
- Two separate outputs per axis for higher speed motions and lower-speed precise movements: 500°/s full scale range (higher speed) 110°/s full scale range (high precision)
- Analog output – 2.0 mV/°/s sensitivity
- ± 1 % Cross Axis Sensitivity
- 3V supply voltage, 7mA supply current
- On-chip temperature sensor

Data Processing Attributes:

- Auto Zero function for bias calibration
- Integrated amplifier
- Integrated low-pass filter

Data Transmission Attributes:

- Analog Output

Cost: < $6

http://www.invensense.com/mems/gyro/idg500.html

3.3.3 Inertial Measurement Unit

An inertial measurement unit (IMU) integrates a multi axis accelerometer, a single or multi axis gyroscope and optionally a magnetometer to track the motion of a rigid body. It gives position, orientation, velocity and acceleration of the object it is mounted to. IMUs can be used on a car body or a locomotive for navigation purposes. It can complement the Global Positioning System (GPS) or can work stand-alone when the GPS signals are unavailable. IMUs also include a processor chip and a signal conditioning unit which can filter raw data from individual sensors and combine data using sensor fusion techniques to give final position, velocity and acceleration in 6 degrees of freedom. This embedded processing capability reduces computational load on the central computer.

IMUs can be in the form of a circuit board with accelerometer, gyroscope and processing chip as individual components or all the sensors can be integrated into one single package, which is now possible with the recent advancements in MEMS technologies (Figure 3-11).

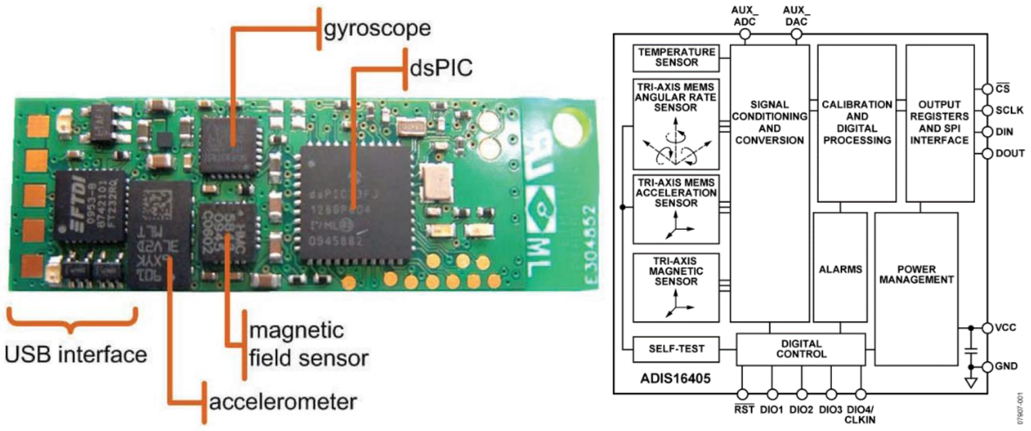


Figure 3-11: IMU board on left (ETH Zurich) and IMU in a single package on right (Analog Devices – ADXL 16405)

The programmable chip permits alarm generation useful for condition monitoring using IMU data. Motion data is available in a variety of formats such as rotation matrix, quaternion, Euler angles etc. DARPA has been working towards more accurate 'TIMU' (Timing & Inertial Measurement Unit) chips which integrate 3-axis accelerometers, 3-axis gyroscope and 3-axis magnetometer with a highly accurate master timing clock that synchronizes sensors and data fusion to give time stamp detailed accurate absolute position.

Low cost IMUs are available from the manufacturers of MEMS sensors to deploy on locomotive or freight cars. The following table lists two choices for inertial measurement units. They are proven design, low cost and widely used in industry and provide flexible options for deployment on railroad cars and locomotive.

Table 3-3: Commercial choices for Inertial Measurement Units

Device and Manufacturer	No. Of axis	Range	Power Requirements	Cost per unit
ADIS16405 Analog Devices	3-axis accelerometer, gyroscope and magnetometer	±18 g ±75 °/sec to 300°/sec ±2.5 gauss	4.75 V to 5.25 V	~ $30 (cheaper in quantity)
MPU 6000/6050 InvenSense	3-axis accelerometer, gyroscope	±2*g*, ±4*g*, ±8*g*, ±16*g* ±250, ±500, ±1000, and ±2000°/sec	2.3 - 3.4VDC	<$15.00 (in quantity) $35 with breakout board

Inertial Measurement Unit – Tri Axial Inertial Sensor with Magnetometer

Producer/Product: Analog Devices (ADIS16405)

Measurands:

- A 3 axis gyroscope, a 3 axis accelerometer, and a 3 axis magnetometer in one package

Hardware Attributes:

- Proven design, 2000g shock survivability
- Small and thin: 4mm x4mm x0.9 mm QFN package
- Factory calibrated for sensitivity, bias, axial alignment etc.
- Operating temperature range: −40°C to +105°C

Sensing Attributes:

- Triaxial, digital gyroscope with digital range scaling ±75°/sec, ±150°/sec, ±300°/sec settings. Tight orthogonal alignment, <0.05°
- Triaxial, digital accelerometer, ±18 g
- Triaxial, digital magnetometer, ±2.5 gauss
- Embedded temperature sensor
- Single-supply operation: 4.75 V to 5.25 V

Data Processing Attributes:

- Signal conditioning that optimizes dynamic performance
- Programmable operation and control
- Alarms for condition monitoring

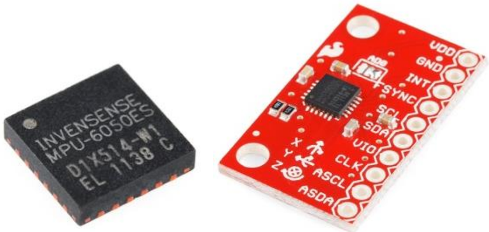
Data Transmission Attributes:

- SPI-compatible serial interface
- Enable external sample clock input up to 1.2 kHz

Cost: Low cost - <$30

http://www.analog.com/en/mems-sensors/mems-inertial-sensors/adis16405/products/product.html#product-documentation

Inertial Measurement Unit (Gyro + Acclerometer)



Producer/Product: InvenSense (MPU 6000/6050)

Measurands:

- 3 axis angular velocity (gyro) and 3 axis angular acceleration (accelerometer). Digital-output of 6 or 9-axis MotionFusion data in rotation matrix, quaternion, Euler Angle, or raw data format

Hardware Attributes:

- Proven design, 10,000g shock tolerant
- Small and thin: 4mm x4mm x0.9 mm QFN package
- Operating temperature: -20°C to 85°C

Sensing Attributes:

- Combines a 3-axis gyroscope and a 3-axis accelerometer on the same silicon die together with an onboard Digital Motion Processor™ (DMP™) capable of processing complex 9-axis motion fusion algorithms.
- User-programmable gyro full-scale range of ±250, ±500, ±1000, and ±2000°/sec
- User-programmable accelerometer full-scale range of ±2*g*, ±4*g*, ±8*g*, and ±16*g*
- *Gyro sensitivity 13.1 to 16.4* LSB/°/sec
- Accelerometer sensitivity 16384 to 2048 LSB/g

Data Processing Attributes:

- MotionFusion™ and run-time calibration firmware
- Integrated 9-axis MotionFusion algorithms access external magnetometers or other sensors through an auxiliary master I²C bus, allowing the devices to gather a full set of sensor data without intervention from the system processor.

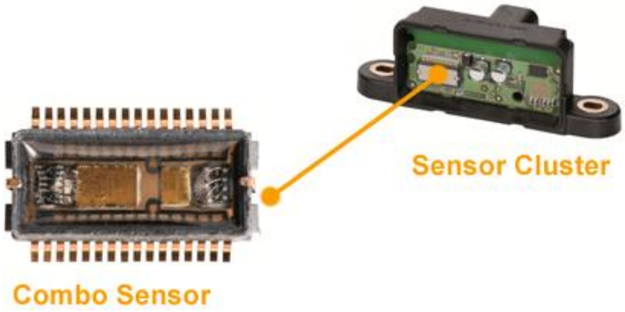
Data Transmission Attributes:

- I²C or SPI. 1kHz sample rate at full power

Cost: $10

http://invensense.com/mems/gyro/mpu6050.html

Sensor Cluster



Producer/Product: Continental

Measurands:

- Vehicle’s current movement status (yaw rate, longitudinal and lateral acceleration and, optionally, pitch and roll rates)

Hardware Attributes:

- Compact design
- Resistance to vibration and temperature
- Operational temperature up to 125°C

Sensing Attributes:

- Acceleration and Yaw rate measurement for vehicle stability
- Capacitive sensors – higher resolution and sensitivity
- High resistance to unwanted frequencies and signal cross talk

Data Processing Attributes:

- Highly integrated signal processing monitors and analyzes all internal signals
- If the system detects a fault, it is saved in a separate, non-volatile memory and can be read using diagnostic equipment

Data Transmission Attributes:

- The verified signals are transmitted to the data bus via a standardized interface (e.g. J1939 interface), which can also be adjusted on a customer-specific basis.

Cost: ~ $30 - $50

http://www.conti-online.com/www/automotive_de_en/themes/passenger_cars/chassis_safety/passive_safety_sensorics/sensor_sensor_system_en/sensor_cluster_en.html

3.3.4 Temperature Sensor

Temperature sensors can be used at multiple locations on a railroad car. Defects in the moving components typically result in a rise in their temperature as the mechanical energy is converted to the heat energy because of high friction losses and impact forces. In the railroad operation, bearing defects increase the temperature in the bearing cup and on the adapter surface. Wheel flat spots cause higher friction resistance to the pure rolling which can result in rise in temperature near the wheel flange surface and near axle region. Temperature sensors can be used to monitor the condition of these components in real-time and raise a precautionary alarm for any signs of overheating and degradation. Moreover, some goods (food, chemicals) require controlled temperature during their storage and transportation. A low cost temperature sensor can be used to monitor the condition inside the car.

The most critical use of the temperature sensor is for real time monitoring of car truck bearing health. The bearing temperature is almost equal to the ambient temperature during normal operation. Defects in the bearing induce vibrations and friction losses which heat up the bearing cone raising its temperature. The bearing temperature can go as high as 150°C above the ambient temperature indicating the risk of complete failure. The bearing adapter surface temperature also rises but there is a lag due to thermal resistance associated with a longer heat transfer path. The adapter surface temperature is typically 15-20°C less than the cup temperature [Kypuros et al., 2011]. Nonetheless, a low cost surface temperature sensor can be used on the bearing adapter for real-time (with some latency) temperature monitoring of the bearing. Temperature rise also depends upon the loading condition of the car and the train speed. Bearings on loaded cars are more prone to quick rise in the temperature and subsequent failure than unloaded cars.

Figure 3-12: Wireless Sensor Node for bearing temperature, INOX LLC [Kypuros et al., 2011]

Temperature sensors can be thermocouple based in which temperature at the junction of two dissimilar metals produces a corresponding voltage drop. Thermocouples provide wide choices of temperature measurement range depending upon the combination of metals used. A K type thermocouple can measure -180 to 1300°C whereas a T thermocouple has a smaller range from -250 to 300°C.

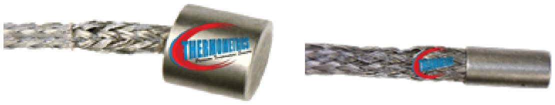
The thermistor based temperature sensor is a type of resistor whose resistance varies with temperature. Thermistors have a higher precision (±0.2°C) for a limited temperature range, typically −90 °C to 130 °C. Thermistors generally use ceramic or polymer materials and differ from a Resistance Temperature Detector (RTD) which uses pure metals. RTDs are useful over larger temperature ranges and are slowly replacing thermocouples in many industrial applications below 600 °C, due to higher accuracy and repeatability.

For real-time monitoring of railroad truck bearings, a low cost temperature sensor (thermocouple or thermistor), capable of measuring -40 to 200°C is suitable. Nominal accuracy (±1 to 2°C) is sufficient for the application. Rugged construction is required for use for the harsh railroad environment. A MEMS based temperature sensor can be used inside the railroad car.

Table 3-4: Commercial choices for Temperature Sensors

Temperature sensor location	**Device and Manufacturer**	**Range**	**Power Supply**	**Cost**
Bearing Adapter	**100 Ω Platinum RTD Thermometrics**	-50 to 260°C	-	~10$ with casing
	RTD element Omega	-50 to 500°C	-	$1 (100 pcs) Casing req.
	Bayonet Thermocouple Omega	-40 to 480°C	-	~$20 in quantity (stainless steel case)
Inside the vehicle	**Vishay** NTCLE100E3103JB0 Thermistor	-40°C to +125°C	Self-Powered	$1.56 (100+ Pcs)
	Analog Devices TMP36 (MEMS)	−40°C to +125°C	2.7V to 5.5V	$1.50

Bearing RTD



Producer/Product: Thermometrics Platinum RTD

Measurands:

- Bearing cup and bearing adapter temperature

Hardware Attributes:

- Miniature design. Sizes from 0.125 inch in diameter and 0.30 in length
- Vibration proof solid design, no moving parts
- Element encapsulation using high temperature epoxy resin. Moisture proof.

Sensing Attributes:

- Platinum RTD 100Ω ±0.12% at 0°C
- Measuring range from -50 to 260°C (-58 to 500°F)
- Tip sensitive thin film technology.

Data Processing Attributes:

- 1.5 to 3 seconds time constant

Data Transmission Attributes:

- 2, 3 (single and double) or 4 (single) wire configuration

Cost: ~ $10 with casing

http://www.thermometricscorp.com/bearing-sensor.html

Bearing RTD Element

Producer/Product: Omega – Thin Film RTD Element

Measurands:

- Bearing cup and bearing adapter temperature

Hardware Attributes:

- Flat (round, cylindrical shapes available), Small Profile Thin Film RTD Element
- 2.0mm x 2.0mm size
- Vibration and shock resistant design
- Insulation Resistance >10Mohms at 20°C

Sensing Attributes:

- Thin film Platinum RTD 100 Ω, 500 Ω and 1000Ω configurations
- Temperature Range -50 to 500°C (-58 to 932°F)
- Maximum Specified Operating Current (1 milliamp for 100Ω, 0.7milliamp for 500Ω and 0.3 milliamp for 1000Ω Elements)

Data Processing Attributes:

- Temperature Coefficient $\alpha = 0.00385\Omega/\Omega/°C$ Nominal

Data Transmission Attributes:

- Platinum Clad Nickel Wire Leads 10 L x 0.2 mm D for resistance measurement

Cost: $1 (100 pcs)

http://www.omega.com/pptst/F1500_F2000_F4000.html

Bayonet Style Thermocouple

Producer/Product: Omega – Bayonet style thermocouple

Measurands:

- Bearing cup and bearing adapter temperature

Hardware Attributes:

- Extruder type Bayonet probe - stainless steel construction
- Straight and right angle thermocouple tip configurations
- Glass braid insulated thermocouple wire

Sensing Attributes:

- Bayonet probes in J, K, T or E type thermocouples
- Service temperature up to 480°C (900°F) (Lower for type T thermocouple)

Data Processing Attributes:

- None

Data Transmission Attributes:

- Analog output voltage correlated to the temperature

Cost: ~ $20 (in quantity)

http://www.omega.com/pptst/BT-000_BT-090.html

Thermistor

Producer/Product: Vishay NTCLE100E3

Measurands:

- Freight/Tank car temperature

Hardware Attributes:

- Radial leaded NTC Thermistor
- Mounting by soldering in any position
- ~ 0.3g weight

Sensing Attributes:

- The device consists of a chip with two solid copper tin plated leads
- Negative temperature coefficient
- Operating temperature -40 to 125°C

Data Processing Attributes:

- Thermal time constant 15s
- Temperature resistance correlation formulae, table and plots available

Data Transmission Attributes:

- Resistance leads

Cost: ~ $0.2 (1000+ pcs)

http://www.vishay.com/docs/29049/ntcle100.pdf

MEMS Temperature Sensor

Producer/Product: Analog Devices TMP36

Measurands:

- Freight/Tank car temperature

Hardware Attributes:

- Available in low cost 3-lead TO-92, 8-lead SOIC_N, and 5-lead SOT-23 surface-mount packages
- Stable with Large Capacitive Loads

Sensing Attributes:

- 10 mV/°C scale factor
- Low Voltage Operation (+2.7 V to +5.5 V), quiescent current < 50 µA
- Operating temperature -40 to 125°C

Data Processing Attributes:

- No external calibration required. Output voltage is proportional to the centigrade temperature with ±2° C accuracy over the −40° C to +125° C temperature range.

Data Transmission Attributes:

- Voltage output that is linearly proportional to the Celsius (centigrade) temperature.

Cost: $0.5 (1000+ pcs)

http://www.analog.com/en/mems-sensors/digital-temperature-sensors/tmp36/products/product.html

3.3.5 Measurement Microphone

A microphone can be used for monitoring a bearing's health based on the acoustic signature of the bearing during operation. Acoustic signals from defective bearings have peaks at frequencies higher than the rotational rate of the bearing. These high frequency peaks correspond to cone defect repetition rate [DOT/FRA/ORD-00/06.II, 2003]. Way-side acoustic detectors are already used by Class I railroads but they do not provide continuous condition monitoring. A low cost onboard microphone near the wheel-axle junction can aid in pre-failure detection of degrading bearings. An acoustic sensor near the brake may also be very useful. It can complement real-time condition monitoring of the brake system.

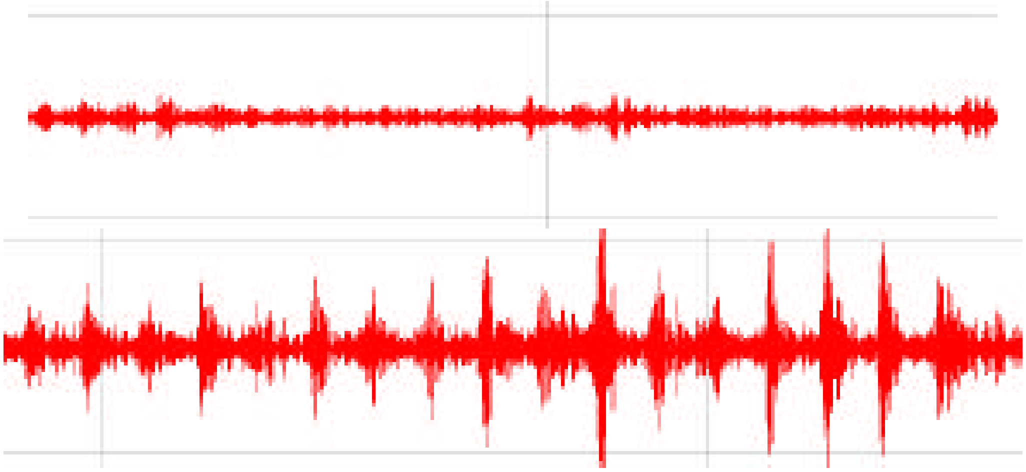


Figure 3-13: Acoustic Signatures from a good bearing (top) and a defective bearing with single outer race spall (bottom) [Smith, 1998]

Microphones based on different working principles are available. Magnetic microphones use a coil in a magnetic field attached to a light diaphragm. Piezoelectric microphones use piezoelectric crystal such as quartz to measure pressure changes in acoustic waves. Fiber optic microphones sense changes in light intensity caused by acoustic waves. Widely used condenser microphones measure change in capacitance caused by pressure variations generated by acoustic waves. MEMS sensors are typically variants of condenser microphone design. They are accompanied with an integrated preamplifier.

The dynamic range and frequency response are two of the most important parameters in the selection of an appropriate microphone for a given application. Dynamic range is the range of sound pressure levels (dB) for which a microphone meets its performance specifications. Higher dynamic range (~ 150 dB) is required in the continually loud railroad environment. Human hearing capability is roughly 140 dB. Frequency range is the range of frequencies in an acoustic wave a microphone can respond to. The audible frequency range for the human ear is from 20 Hz to 20 kHz.

A microphone near a bearing will experience a wide range of acoustic frequencies. Low frequency components from an aerodynamic bow wave can be rejected with a high pass filter (say rejecting less than 8 Hz but still allowing low frequency audible signals ~20Hz). Acoustic signals from defective bearings show peaks at frequencies corresponding to the defect repetition rate (30 Hz to 100 Hz). High frequency sounds (>15 kHz) were also distinctly observed in acoustic signals coming from defective bearings. A microphone with high frequency range (dc to 40 kHz) is most desirable (as used in wayside inspection). A low cost microphone in the audible range (20 Hz to 20 kHz) may also be sufficient for bearing condition monitoring. High sample rate (>80 kHz) is required to fully support high frequency content. A good signal to noise ratio (>40dB) and a wide operating temperature range is desired. A rugged casing is required for microphones in harsh railroad environment.

Table 3-5: Commercial choices for Microphones

Device and Manufacturer	Sensitivity	Range	Power Requirements	Cost per unit
4944 **Pressure Field** **Bruel & Kjaer**	0.9 mV/Pa -60 dBV	4 Hz to 70 kHz		
ADMP401 **Omnidirectional** **Analog Devices**	7.9 mV/Pa -42 dBV	75 to 15 kHz	1.5V – 3.3V <250 uA	$3.16

Microphone

Producer/Product: Bruel & Kjaer – Pressure field microphone

Measurands:

- Acoustic waves – Bearing sound

Hardware Attributes:

- ¼" diameter, rugged design
- Flush mounted
- Laser-welded diaphragm on the microphone housing ensures that the sensitivity is resistant to rough handling
- Operating Temperature: –40 to +150°C (– 40 to +302°F)

Sensing Attributes:

- Prepolarized pressure field microphone. 5 pF Capacitance
- High level, High frequency measurements
- Dynamic range: 46 dB(A) – 170 dB, Frequency: 4 – 70 000 Hz
- Sensitivity: 0.9mV/Pa

Data Processing Attributes:

- The sensitivity has been optimized to allow measurements of high sound pressure levels without clipping in the built-in CCLD preamplifier.

Data Transmission Attributes:

- Analog voltage output, 0.9 mV/Pa sensitivity

Cost: moderate

http://www.bksv.com/Products/transducers/acoustic/microphones/microphone-cartridges/4944

Omnidirectional MEMS Microphone

Producer/Product: Analog Devices ADMP 401 Omnidirectional Microphone

Measurands:

- Sound waves – near bearing and brakes

Hardware Attributes:

- 4.72 mm × 3.76 mm × 1.0 mm surface-mount package
- Bottom-ported omnidirectional MEMS Sensor
- Solder compatible with no sensitivity degradation
- Operating Temperature: –40 to +85°C

Sensing Attributes:

- Flat frequency response from 100 Hz to 15 kHz
- Sensitivity of −42 dBV
- High Signal to Noise Ratio – 62dBA
- Supply voltage 1.5 to 3.3V, Low current consumption of <250 µA

Data Processing Attributes:

Data Transmission Attributes:

- Single-ended analog output

Cost: $3.16

http://www.analog.com/en/mems-sensors/mems-microphones/admp401/products/product.htm

3.3.6 Proximity Sensor

A proximity sensor detects the presence of an object in the ‘vicinity’ of the sensor. The vicinity is defined as a nominal distance range from the sensor in which the object’s presence can be detected. Many proximity sensors also report the object distance in that range. Proximity sensors can be useful at multiple locations on a railroad car. A proximity distance sensor can be used to evaluate the brake piston travel in real-time. Currently the railroad industry does not have a mechanism to determine whether the air brakes are applied effectively in real-time, which poses a serious safety concern. Moreover, current manual inspections are time consuming and prone to human judgment error which can lead to catastrophic accidents. A simple low-cost proximity sensor can measure the brake piston stroke and relay the information to the locomotive engineer in real-time. It can check for debris caught between the brake shoe and the wheel of the rail car restricting piston travel. The sensor can also indicate potential wear on a brake shoe for preventive maintenance.

A proximity sensor may be useful for detecting car door lock status. It can raise an alarm if a container carrying high value goods has been opened. A Hall Effect sensor or a low cost proximity switch can be adequate for this purpose.

Another use of a proximity sensor would be to measure the distance between the coupler and the striker on a car. Draft gears absorb coupler impact energy and provide damped slack between the coupler and the car (up to 6 inches per car). This compliance reduces in-train forces and cycling events. Relative displacement between the coupler and the striker on the car can be a measure of impact/shock during train makeup. A proximity displacement sensor will provide a low cost method to estimate the coupler forces compared to a force/load sensor.

Figure 3-14: Proximity sensor for brake piston stroke measurement [FRA Research Results, 2009]

Proximity sensors are based on variety of operating principles. Inductive proximity sensors are based on electro-magnetic induction and are best suitable for metallic objects. Capacitive proximity sensors use variation in capacitance between the sensor and the object. They can be used for non-metallic objects like plastic or wooden materials. Infrared proximity sensors use beam reflection and changes in ambient conditions to allow sensing of the objects and measure object distance. Ultrasonic range finders emit sound waves (ultrasonic) and measure time of flight to estimate the object distance. Infrared and ultrasonic proximity sensors typically have larger range.

For the train's pneumatic brakes, piston travel must provide brake shoe clearance when brakes are released. The piston travel must be adjusted between 6 to 9 inches and it must not exceed 10 ½ inches for body mounted brake cylinders. A low cost infrared or ultrasonic based proximity sensor with suitable range can be chosen for real-time monitoring of brake piston travel and brake effectiveness. These sensors are placed under rail cars and are subjected to debris, wide range of temperature and contact with snow, dust, water and oil. The system design should be rugged and useful in all weather conditions.

Table 3-6: Commercial choices for Proximity Sensors

Device	**Range**	**Interface**	**Power Supply**	**Cost**
GP2Y0A21YK GP2Y0A21YKoF **SHARP** Infrared Sensor	10 cm - 80 cm Higher Range version 20cm to 150cm	Analog	4.5 to 5.5V 30mA	$11.16 (100+ Pcs)
VCNL3020 **Vishay Semiconductors**	0.1 to 20 cm	16 bit, I^2C	2.5 to 3.6V	$ 1.51 (1000 pcs) Rugged casing required
MB Series MaxBotix Ultrasonic Sensors	15 cm to 650 cm Multiple options available	Analog and I^2C	2.5 – 5 V	~$25 Rugged options ~$70

Proximity Sensor

Producer/Product: SHARP (GP2Y0A21YK)

Measurands:

- Distance/proximity measurement

Hardware Attributes:

- 29.5×13×13.5 mm
- Operating Temperature -10 °C to +60 °C

Sensing Attributes:

- Optoelectronic device – wide angle distance measurement sensor composed of an integrated combination of PSD (position sensitive detector), IRED (infrared emitting diode) and signal processing circuit.
- Range: 10 to 80 cm, higher ranges up to 150cm and 550 cm
- Analog output that varies from 3.1V at 10cm to 0.4V at 80cm. Digital output option available
- Typical response time: 39 ms, Typical start up delay: 44 ms
- Supply voltage : 4.5 to 5.5 V, Average Current Consumption: 30 mA
- Detection Area Diameter @ 80 cm: 12 cm

Data Processing Attributes:

- None indicated

Data Transmission Attributes:

- Analog Output

Cost: $10.0

http://www.sharpsma.com/webfm_send/1208

Surface Mount Proximity Sensor

Producer/Product: Vishay (VCNL 3020)

Measurands:

- Distance/proximity measurement

Hardware Attributes:

- Surface mount – 4.9×2.4×0.83 mm
- Operating Temperature -10 °C to +60 °C

Sensing Attributes:

- Built-in infrared emitter and photo-pin-diode for proximity sensing
- Range: 1 to 200 mm, 16 bit resolution
- Up to 250 measurements per second
- Supply voltage : 2.5 to 3.6 V, Current Consumption: 10 to 200 mA, Standby 1.5 µA

Data Processing Attributes:

- Integrated signal conditioning IC
- Interrupt function

Data Transmission Attributes:

- Communication via I^2C interface, 16 bit

Cost: $1.51

http://www.vishay.com/docs/84150/vcnl3020.pdf

3.3.7 Pressure Sensor

Liquid and gaseous commodities are transported in tank cars on railroad. These tank cars can be pressurized or non-pressurized and many times they carry hazardous materials. DOT-111 are non-pressure tank cars which carry a wide spectrum of liquids including ethanol and crude oil. DOT-112/114 is a type of tank car designed to transport pressurized gases, frequently these gases are toxic. As a train consisting of tank cars passes through hot and cold weather and curved tracks, it is necessary to understand the thermodynamic behavior of the products inside the car. Pressure relief devices are already in use on tank cars as a safety measure. It is proposed to use low cost pressure sensors which can give near real-time updates on the pressure and temperature condition inside the car. Alarms can be raised if unusual pressure is built up or a temperature rise is sensed inside the tank car. Submersible pressure sensors can also be used for liquid level measurement inside the car. For example, gradual pressure drop can indicate leak in the car.

A pressure sensor can also be used to monitor the air pressure in the main brake line or the brake cylinder. The standard brake pipe pressure is 90 psi (80 psi or 100 psi in some cases). The minimum differential between the main brake line and the reservoir is required to be 15 psi when triple valve is in ‘running’ (apply) position. To apply the brakes, the main brake line pressure is reduced which triggers the car reservoir air to be used in the cylinder to push the piston. An Electronically Controlled Pneumatic Brake (ECP) system is designed for quicker propagation of pressurized air to and from the brake cylinders. It takes a finite amount of time to re-charge the reservoir after releasing the brakes and brakes are not fully available during this time. This is frequently a primary cause of railcar runaway. It is suggested to monitor brake air pressure levels in real-time and relay this information to the locomotive train engineer to avoid most runaways. In addition, the required braking effort is different for loaded and empty cars. Loaded cars require more braking force but at the same time, heavy braking on empty cars can lead to sliding wheels which results in flat spots on the wheels. Currently a load sensing arm passively controls opening and closing of the exhaust limiting valve to control the pressure in the cylinder based on the car load. A cargo load sensor along with air brake pressure sensor information can be used intelligently to apply suitable brake forces based on real-time conditions. This will improve the train braking performance.

Figure 3-15: Brake pressure transducer on instrumented research truck [FRA, 2010]

Pressure transducers can be based on piezoresistive (silicon based), capacitive, piezoelectric or optical principles. Low cost board mounted pressure sensors, which are also proposed for use in vehicle tires, can be selected for brake line and cylinder pressure. These can also be used for non-corrosive, non-ionic gaseous commodities in the tank car. Rugged, submersible level sensors are suitable for non-pressurized tank cars carrying a wide spectrum of liquids. A wide range of pressure sensors is available from manufacturers such as Freescale Semiconductors, STMicroelectronics, Omron Electronics, Honeywell, American Sensor Technologies, Omega etc. (see Table 3-7).

Table 3-7: Commercial choices for Pressure Sensors

Device Manufacturer	**Range**	**Interface**	**Power Supply**	**Cost**
SM5420C Board Mounted Pressure Sensor **Silicon Microstructures**	Absolute 15,30,60 & 100 psi	High millivolt output	5V 1mA	$1.66 (1000+ Pcs)
NBP Series Board Mounted Pressure Sensor **Honewell**	Absolute and gage 15,30,60, 100 & 150 psi	Unamplified millivolt output	1.8 V to 12 V 1.5 mA	$ 5.61 (1000+ pcs)
AST4530 Submersible Pressure Sensor **American Sensor Technologies**	5,7.5,10,20,30 psi gage	Voltage or mA output	10V to 28 V 20 mA max (3mA for voltage output)	~$10 in quantity

Board Mounted Pressure Sensor

Producer/Product: Silicon Microstructures (SM5420C)

Measurands:

- Pneumatic air pressure

Hardware Attributes:

- Small outlined SO-8 packaged pressure sensor
- Surface mount design
- Ported and non-ported configurations
- Operating Temperature -40 °C to +125 °C

Sensing Attributes:

- MEMS piezoresistive pressure sensing die (SM5108C)
- Absolute full-scale range 15, 30, 60 & 100 psi
- Supply voltage : 5V nominal, 1mA nominal current draw

Data Processing Attributes:

- None

Data Transmission Attributes:

- High millivolt output (65-135mV analog)

Cost: $1.66 (1000+ quantity)

http://www.si-micro.com/upload/product/pdf/SM5420C_Datasheet2.pdf

Submersible Pressure Transducer

Producer/Product: American Sensor Technologies (AST4530)

Measurands:

- Hydrostatic pressure and liquid level in rail tanks.

Hardware Attributes:

- Made of PVDF material and a PTFE diaphragm – designed for corrosive liquids.
- Operating Temperature 0°C to 60 °C
- Compact, rugged built, more than 50 million pressure cycles
- Shock and vibration resistant

Sensing Attributes:

- PTFE diaphragm, compatible with many corrosive liquids and gases
- <±0.5% Best Fit Straight Line accuracy
- 5,7.5,10,20,30 psi gage
- Supply voltage : 10V to 28 V, 20 mA max (3mA for analog voltage output sensor)

Data Processing Attributes:

- None

Data Transmission Attributes:

- Submersible PVDF cable
- 0.5-4.5V ratiometric, 1-5V or 4-20mA output options available.

Cost: ~$10 in quantity

http://www.astsensors.com/files/pdf/AST4530-PVDF-submersible-pressure-transducer.pdf

3.3.8 Strain Gages

Strain gages measure strain on an object. Strain is the deformation of a body under applied load (force), mathematically calculated as the fraction of change in length over original length. Strain gages are widely used as primary sensing elements for force and pressure measurements. They are typically based on the principle of change in resistance of the gage material (conductor) due to deformation.

Strain gages can be used at multiple locations on a railroad car to give information about dynamic loading and impact forces on the freight car body and the car components. Couplers can be instrumented with strain gages to measure longitudinal forces resulting from braking, acceleration, and jerks in the train consist in the longitudinal direction. Shear gages mounted on the sides of the coupler can measure vertical coupler forces arising from track irregularities such as switches on the track, dips and bumps on the rails etc. For tank cars the coupler vertical force on the stub sill is believed to be major cause of cracking of stub sills [FRA – Instrumented Tank Car, 2004]. A pair of strain gages on the bolster side – underneath the bearing and bottom surface can provide sensing signals for the side bearing loads and the bolster center bowl load. Wheels can also be instrumented with strain gages to measure vertical, lateral and longitudinal forces at the wheel/rail interface. These forces indicate impact/shocks on the truck due to track irregularities.

Typical strain gages are slender (wire like) metallic resistive elements which change resistance, on compression, or elongation (resistance is directly proportional to the length and inversely proportional to the area of the element). Unbonded strain gages consist of a wire stretched between two points on the test specimen. Bonded strain gages are thin wires arranged in a coplanar grid. The grid is bonded to a thin base or carrier and attached directly to the object surface. The modern strain gages are metallic foil type gage, produced by photo-etching techniques. They have more surface contact area to cross section area ratio than a wire grid strain gage to facilitate the dissipation of induced heat. Hence they are more stable under extreme temperatures and prolonged loading.

Figure 3-16: Strain gages mounted on the couler and bolster for test purposes [FRA – Instrumented Tank Car, 2010]

Figure 3-17: Vertical load adapter with strain gages to measure vertical wheel forces [FRA – Instrumented Tank Car, 2010]

Semiconductor strain gages use piezoresistive properties of silicon (or germanium) to measure strain. They are more suitable for measurements of small strains and provide better sensitivity and higher level output. But semiconductor gages can be expensive; they are more sensitive to temperature changes and are more delicate than foil gages (see Table 3-8).

Table 3-8: Comparison between metal and semiconductor strain gages [Kester, 2010]

Parameter	**Metal Strain Gage**	**Semiconductor Strain Gage**
Measurement Range	0.1 to 40,000 □□	0.001 to 3000 □□
Gage Factor	2.0 to 4.5	50 to 200
Resistance, □	120, 350, 600, …, 5000	1000 to 5000
Resistance Tolerance	0.1% to 0.2%	1% to 2%
Size, mm	0.4 to 150 Standard: 3 to 6	1 to 5

The typical strain measurements are in the order of a few millistrains (10-3). The corresponding resistance change is also small and is usually measured using a Wheatstone bridge. Strain gages are also highly sensitive to temperature changes. In general, electrical resistivity of strain gage metal increases with temperature. In addition a strain gage may also respond to thermal expansion of the material to which gage is attached. A slight change in temperature can generate a measurement error of several microstrains. Strain gage manufacturers minimize sensitivity to temperature to some extent by compensating for the thermal expansion of the material for which the gage is intended. Use of Wheatstone bridge or ‘dummy gages’ further minimize the effect of temperature as any changes in temperature affect all the gages in a bridge in the same way. Hence the absolute ratio of their resistance does not change.

Table 3-9: Commercial choices for Strain Gages

Device Manufacturer	**Resistance**	**Strain Range**	**Cost**
CEA Series **Vishay Precision Group**	350 □	±5%	$6.25 (5000+ Pcs)
LWK Series **Vishay Precision Group**	350 □	±5%	~$15 (Weldable, Wide operating temperature range)

Piezo Sensor – Piezo Film Elements

Producer/Product: Measurement Specialties, Inc (DT Series)

Measurands:

- Strain/deformation measurement. Sensing direct contact force. (Multi-purpose use – vibration sensing, impact sensing, deformation sensing etc.)

Hardware Attributes:

- The piezo film element is laminate to a sheet of polyester
- Unshielded or shielded option available. If shielding is required, the sensor can be enclosed in a proper environment.
- Varying sizes available. Eg. 20 mm × 3 mm× 110 μm
- Operating temperature: 0°C to +70°C

Sensing Attributes:

- The piezo film produces a useable electrical signal output when forces are applied to the sensing area
- Output Voltage: 10 mV-100V depending on Force and Circuit Impedance
- Minimum impedance: 1 MΩ. Preferred impedance: 10 MΩ and higher

Data Processing Attributes:

- Only sensing element. Amplifier and A/D converter circuit board options available

Data Transmission Attributes:

- The dual wire lead attached to the sensor allows a circuit or monitoring device to process the signal

Cost: Low cost ~ $10

http://www.meas-spec.com/product/t_product.aspx?id=5435
http://www.meas-spec.com/piezo-film-sensors/piezo-film-elements.aspx

Many other sensors can be useful on the train for real-time awareness about operating conditions. Locomotives have already been equipped with a variety of sensors. Other than the sensors listed above, a low cost vision sensor can be used to estimate the ground velocity of the train using optical flow. Angular velocity sensors at the wheels can measure the rotational wheel speed and calculate the wheel slip by comparing it with the linear speed of the train. Wheel slip information is extremely useful for traction control and wheel condition monitoring. Leak detectors on tank cars are crucial for safe transportation of toxic gases. Temperature and humidity sensors are important for monitoring conditions inside the cars transporting food and agricultural products.

Similar sensors can be used at multiple locations on railroad cars to get useful information. For example a proximity sensor can measure brake piston travel when it is mounted on the brake cylinder. Another proximity sensor can estimate total load on the car by measuring the suspension spring (coil) deflection. A microphone at the bearing can be used to detect impeding bearing failures. Another microphone near the brake shoe can be useful to evaluate braking action (look for squeaking noise etc.). The idea is to list as many sensing choices as possible. Some of the sensors are simple and give direct relevant information. Some are more complex and useful information may need to be inferred from the indirect measurements. The goal should be to equip freight trains with as many low cost sensors as possible to get maximum real-time awareness about the operating conditions and to improve performance and efficiency by providing continuous condition monitoring of all the components.

Table 3-10 gives a summary of the sensors discussed for railroad cars. The importance rank on a scale of 1 to 10 indicates that sensing domain’s usefulness. A rank of 10 represents a critically useful and is recommended to be deployed on the cars as soon as possible. The maturity column gives a ranking based on the current state of technology for the sensing domain. A rank of 10 indicates that mature, industry proven low cost commercial sensors are available for that sensing domain.

Table 3-10: Summary of Sensors Proposed for Railroad Cars

Sensor	**Location/Use**	**Importance/ Critical**	**Maturity**	**Commercial Sensor Options**
Accelerometer	Car Body – Lateral Hunting and Car Dynamics	8	8	MMA8452Q Freescale Semiconductor ADXL 345 Analog Devices
	Bearing – Condition Monitoring	10	8	ADXL193 Analog Devices MMA81XXEG Freescale Semiconductor
Gyroscope	Car Body – Track Switching	8	7	L3G4200D STMicroelectronics IDG500 InvenSense
IMU	Car Body - Navigation	9	8	ADIS16405 Analog Devices MPU 6000/6050 InvenSense
Temperature Sensor	Bearing – Condition Monitoring	10	6	100 Ω Platinum RTD Thermometrics Bayonet Thermocouple Omega
	Cargo/Tank Car	6	8	Vishay NTCLE100E3103JB0 Thermister TMP 36 Analog Devices

Table 3-10 continued …

Sensor	Location/Use	Importance/ Critical	Maturity	Commercial Sensor Options
Microphone	Bearing – Condition Monitoring	10	6	4944 Pressure Field Bruel & Kjaer
	Brake – Condition Monitoring	4		ADMP401 Omnidirectional Analog Devices
Proximity Sensor	Brake Cylinder Piston Travel Car Door Lock Status	7	4	GP2Y0A21YK GP2Y0A21YKoF SHARP Infrared Sensor
				VCNL3020 Vishay Semiconductors
				MB Series MaxBotix Ultrasonic Sensors
Pressure Sensor	Tank Car Air Brake System	7	4	SM5420C Board Mounted Silicon Microstructures
				NBP Series Board Mounted Honewell
				AST4530 Submersible American Sensor Technologies
Strain Gages	Coupler Forces Wheel Forces	4	2	CEA Series Vishay Precision Group
				LWK Series Vishay Precision Group

Based on the study of sensors for railroad cars, the following important conclusions are made to develop a multi-sensor architecture for freight trains.

- It is concluded that a vibration sensor, a temperature sensor and a microphone are extremely critical for onboard bearing defect detection and continuous condition monitoring. Mature technologies exist for these sensors and low cost commercial options are available and viable for deployment on railroad car bearings. A rugged microphone with higher sound level measuring capability is desired. The sensor choices listed in Table 3-10 are low cost sensing elements. They may need a rugged casing in harsh railroad environment.
- Inertial Measurement Units (IMUs) integrate multi-axis accelerometer and gyroscope and are being widely used in industries such as automotive, consumer electronics etc. IMUs are low cost and are highly recommended on railroad cars or every locomotive. They can augment GPS capabilities.
- Several options are available for switch like proximity sensors (Hall effect based) at low cost (~$1 to 2). But sensors which give continuous distance measurements (Ultrasonic or Infrared) are typically expensive (~ $25). Hall effect based sensors are suitable for monitoring door lock status.
- Immediate attention is needed for development of low cost devices for force measurement. Strain gage instrumented couplers and wheel sets provide important dynamic information, but strain gages are temperature sensitive and susceptible to degradation over continuous prolonged loading and railroad environments. Current commercial options for force measurements were also found to be expensive to install on every car.

- With the rise in the number of onboard sensors, power consumption, sensor network and communication, and efficient data management are some of the issues that come into play in the freight train environment. They are discussed in more detail in the next section

3.4 ONBOARD SENSOR POWER REQUIREMENTS

It is always advantageous to use as many sensors as possible to enable full awareness about a railroad car's operational conditions. This sensor suite will require a continuous and reliable source of electric power for operation. Electric power is available on each car on passenger trains through overhead lines or from an electric line running through the train. Current freight trains do not run such an electric line through the train. Hence it is essential to have a local power source on each car. An onboard low-cost energy harvester should be used to generate the power. It would energize an onboard battery pack which would provide continuous on-demand power to the network of sensors and data transmission units. The onboard energy harvester is desired to be low-cost, reliable and be able to retrofit into the existing system. It should ideally be an add-on module and permit faster maintenance and repair with quick change out of critical components.

Most energy harvester designs for railroad cars convert kinetic energy of the axle/wheel or truck to electric energy. Special generator bearings (wheelset generators) are available which integrate into the existing axle box housing. They consist of a modified axle cover acting as a rotor and the housing acting as a stator. Some bearings are also equipped with a temperature sensor and an accelerometer and transmit data over radio frequency to a receiver on the car or locomotive. Wheelset generators produce nominal power of three watts with a selectable voltage of 12 or 24 volts [Schaeffler AG, 2012]. The Federal Railroad Administration funded OBMCS (Onboard Monitoring and Control Systems) project which uses a Timken generator bearing and a deep cycle 12-volt marine battery power for onboard sensors and actuators. At 50 miles per hour, the Timken generator bearing produces about 24 watts of power [Edwards, 2005].

Figure 3-18: Schaeffler AG’s TSS-F wheelset generator [www.ina.de]

Current wheelset generators are expensive and it is not cost effective to install them on every freight car. Moreover their maintenance and repair may require special effort and be time consuming. Tesar [Tesar, 2012] suggests a linkage assembly to amplify (5x) the vertical bolster motion in the truck spring assembly. Motion of the coupler rotates the crank. A star compound gear train and a one way clutch converts oscillatory motion to continuous rotational motion of up to 2000 RPM. One other design uses a friction wheel and/or gear train to achieve rotor speed up to 5000 RPM which could easily produce about 100 to 200 watts [Tesar, 2012].

Solar energy and wind energy are also potential options. Photo voltaic panels were installed on Italian rolling stock (two locomotives and three freight coaches) as auxiliary power units [PVTrain, 2005]. They can keep the onboard accumulator (batteries) charged even when the train is stopped and no kinetic energy is available. It is essential that the energy harvester module be remarkably simple, rugged, easily replaced/maintained by the railroad crew and be cost effective (ideally <$120 in quantity).

A suite of twenty sensors listed above may require up to 10 watts of power. To reduce the power requirements, self-energizing or low power consuming sensors are preferred. Many sensors have an idle state or sleep mode where the power consumption is minimal when no measurements are taken. In addition to the sensors which measure raw data, data processing and data transmission units may require additional (20 to 30) watts power. Wireless transmission units are power hungry. Appropriate sampling frequency, efficient information flow and data management (from individual sensors to a microchip on the car to the locomotive) can greatly reduce power consumption.

3.5 FREIGHT TRAIN SENSOR INTEGRATION AND DATA MANAGEMENT

Multiple sensors deployed onboard a freight car give a wide variety of data. It is crucial to manage this large quantity of raw data acquired in real-time and to convert it into useful information. Sensors can be grouped based on the information they give on specific component/domain in a freight car. Sensors are inherently noisy. Data from multiple sensors can be integrated or correlated to increase confidence in the measurements. Various methods exist in information and estimation theory (Kalman filter, particle filters, Bayes reasoning etc.) towards integrating data from multiple sensors and inferring the lost data. Multiple sensors also provide fault tolerance and eliminate single point failures. The following examples in the realm of multiple onboard sensors for a freight car give a better understanding of sensor integration and lays the foundation for system intelligence.

- An accelerometer, a microphone and a temperature sensor are suggested on the bearing for continuous condition monitoring. Any of the three sensors can individually detect bearing defects, at different levels. State of the bearing can be estimated by weighing data from each sensor based on their accuracy, sensitivity to the bearing defects and bearing defect detection regime. For example temperature may be normal at an early stage of the defect. But acoustic and vibration signals can indicate impending bearing failures early on. Similarly some defects may not result in distinct vibration pattern but the bearing cup temperature may rise. A simple Kalman filter can be implemented to fuse data from three sensors to get the state of the bearing. Note that the measurements from three sensors can be asynchronous and at different sampling frequencies (see Section 3.5.1). Analytical or empirical relationships among data from three sensors can be used to generate a Bayesian network of bearing sensors. The time history of data can be used to discard any outlier measurement, thus reducing false alarms.
- Onboard gyroscope and accelerometer data can be integrated to give curvature of the track. Angle/tilt estimation by integrating gyroscope output (angular velocity) accumulates null bias error as the integration period is increased. The gravity signal from an accelerometer can be used to correct the inclination measured using a gyroscope. The Gyroscope and the accelerometer together can sense track switching and provide information about train location among parallel tracks.
- The brake system can consist of a proximity sensor, a microphone and a pressure sensor. Each sensor can detect different kinds of faults or problems that could

occur in the air brake system. The proximity sensor can measure the brake piston travel and check for any debris caught under the shoe which can potentially restrict piston travel and affect braking action. Acoustic signature from a microphone may indicate braking performance (rough or smooth). A pressure sensor can monitor cylinder and valve pressure. Lower cylinder pressure results in lower braking force. Lower air flow rate can slow down the piston movement. This can also be confirmed by differentiating the piston stroke measurements from the proximity sensor. Experimental data from all three sensors during normal braking operation and in tests with induced faults can help correlate sensor information. Lost data due to a sensor fault can be inferred using these correlations. Thus providing multiple ways to assess the condition of the braking system [Krishnamoorthy, 2010].

- Load on the freight car can be directly measured using a load sensor. In addition, proximity sensors on the bolster can measure suspension coil compression to give an estimate of the load. Proximity sensors on both sides of the car can give information about load distribution on the freight car and can corroborate dynamic response measurements (roll and pitch) from onboard accelerometers and gyroscopes.
- Freight car component condition and behavior depend heavily upon speed of the train and loading condition of the car. For example a defective bearing can heat up faster for a loaded car than for an unloaded car. Impact forces due to wheel and track irregularities (such as wheel flats) are higher at higher speed of the train. Wheel flats may not produce large impact forces at lower speeds. Bearing adapter temperature is affected by the environmental temperature and the speed of the car

which provide cooling effect. An intelligent system should take all these factors into consideration (temperature, speed compensation) during condition monitoring of a freight car and the potential for raising an alarm for faults.

3.5.1 Network of Sensors and Data Management

An important consideration for a multi-sensor architecture in railroad cars is connecting sensors to a central processor in each car and relaying information to the locomotive or other remote nodes. Many network topologies such as Star, Bus, Ring arrangements are standard in industries. Several network protocols exist to connect sensors and actuators in the system. AS-i (Actuator Sensor Interface) uses a two conductor cable to connect simple I/O devices in automation. I^2C bus by Phillips Semiconductors is intended to connect microcontrollers with peripheral devices over a serial bus. BiSS – Bidirectional Serial Synchronous interface by iC-Haus provides digital serial communication with time-synchronous data capture for all sensors, fast data transmission with integrity verification (secure communication), and plug & play capability [Quasdorf, 2003]. The FRA OBMCS project uses CAN (Controller Area Network) technology to seamlessly integrate advanced components with the onboard monitoring system. The CAN bus was developed by Robert Bosch GmbH in 1980s to provide simple, prioritized message based communications among sensors in automotive applications. It is now widely used in other industries such as aerospace, automation, etc. CAN bus signals are transmitted in a twisted pair (preferably shielded) cables to minimize RF emissions and interference.

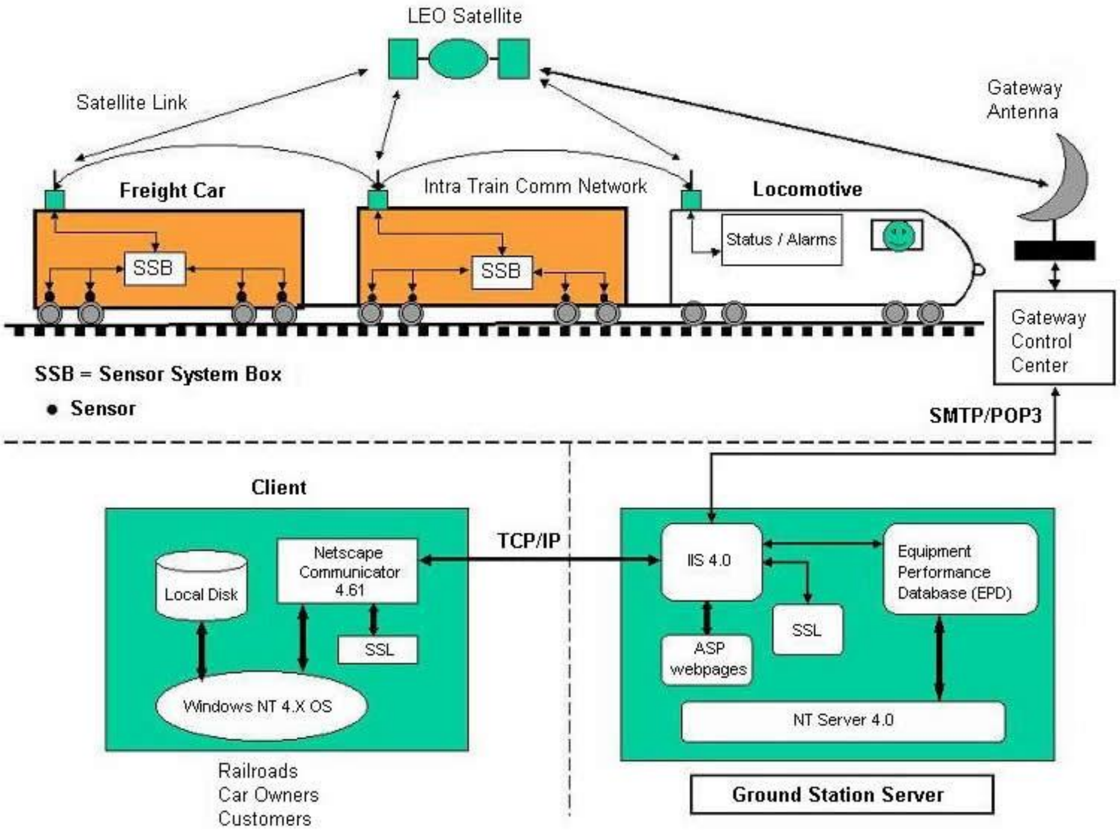


Figure 3-19: FRA On-Board Condition Monitoring System's communication architecture [Edwards, 2005]

The selected network topology and communication protocol on a railroad car should reduce cable complexities and make information flow efficient to reduce power consumption. Connecting all onboard sensors individually to a central processor on each car would require many cables and increase the cable lengths. Other than cabling complexity, long running cables carrying analog signals are susceptible to signal degradation. Moreover, such an arrangement (Star to point topology) increases computational load on the central processor. More interrupts are needed to manage all the sensors individually which also results in more power consumption. Hence the sensor network should be distributed (at least partially) in nature, grouping all the sensors on a sub system and a low power local processing unit dedicated to each sub system. For example a bearing can have an accelerometer, a microphone and a temperature sensor. Accelerometer and microphone measurements are required at high sampling rate (~50 kHz). It is inefficient to sample at such a high rate from the central processor which has to deal with four bearings per car and other onboard sensors. It is suggested to use a local chip on the bearing (say microchip PIC186585 used in OBMCS) with digital I/O and A2D converters. The chip can be connected via a CAN bus to send information over a single twisted pair to the central processor. This low-cost local processor (commercially available at ~$10) handles raw data coming from the accelerometer, the microphone and the temperature sensors on the bearing, performs necessary digital signal processing, and classifies any potential bearing defects. Only the results of the classification of possible defects and the alarms for impending defects should be transmitted to the central processor. The measurement sampling frequency should be high enough to measure all the frequency components but should avoid unnecessary sampling to reduce power consumption. For example the microphone or the accelerometer on the bearing may require up to 50,000 samples a second but it may be sufficient to take temperature readings only every 2 to 4 seconds. To further reduce the power consumption, CAN transceivers can be on standby mode and transmit messages only at an extended time interval, say every 15 or 20 seconds for bearing status and only upon state change for the brake system (edge triggered interrupt). Such a custom approach is critical to limit any unnecessary drain on the power system and to stay within the available power resources. Thus all the sensor sub systems (bearing sensors, brake system sensors, car dynamic response sensors) can have a local processor (a microcontroller) communicating with the central processor (one per car) over the CAN bus (or any other efficient communication protocol) running at a reduced clock speed.

Each car's central processor can send information to the locomotive about state of the car and its sub components over wireless radio link. Each car in the train consist should have a unique ID in the intra train network (may be GPS location based). The wireless radio link information is received on a locomotive computer which can be running a visualization software to display the state of the critical car components to the engineer. Thus the train engineer is always aware of the train condition in near real time and can make informed and timely decisions. Alarms are triggered for any impending faults. Train data can possibly be reported to a web server over the internet to get access from a remote monitoring facility.

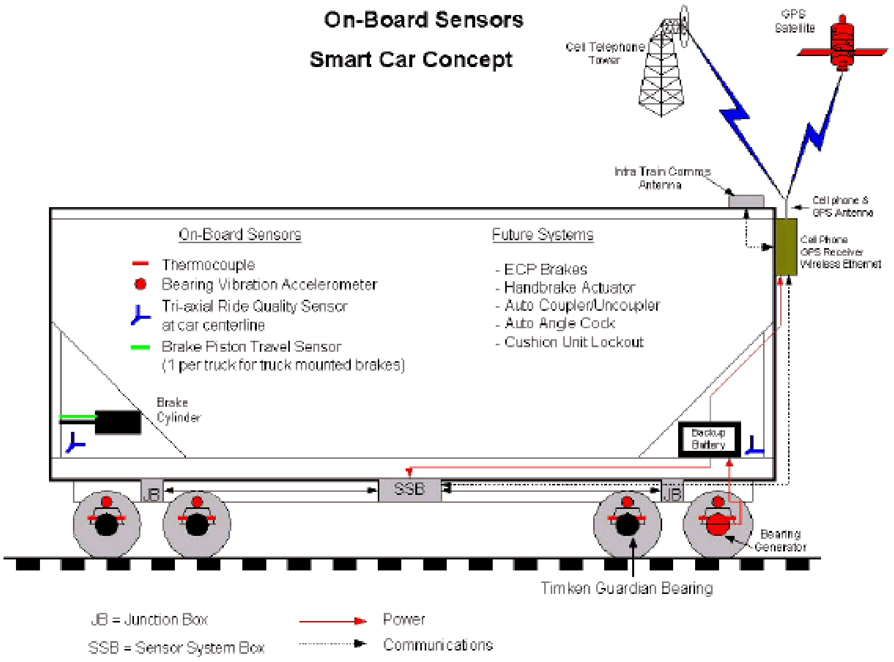


Figure 3-20: FRA On-Board Monitoring and Control System [Edwards, 2005]

This chapter discussed multi-sensor environment for freight train system. It is established that the real-time data from multiple sensors will assist in improving performance (efficiency) of a moving train and enable the scheduling of timely maintenance of degrading components, thus reducing downtime and catastrophic failures due to faulty components. In the present research, sensing requirements for railroad cars were evaluated and suitable sensor technology, current state of the art and low cost commercial sensor options are suggested for railroad operators to make informed decisions. In addition to various sensors, issues such as power consumption and onboard power source in the form of energy harvester, sensor network and communication, and efficient data management in freight train system were also discussed in the chapter.

Chapter 4: Sensors for Vehicle Systems

Vehicles are arguably one of the most complex and essential machine systems used by human beings on a daily basis. Vehicle technology has advanced significantly over the years - from improvements in engine fuel efficiency and power delivery to in-car comfort and safety of the operator. The technology is now moving towards more efficient hybrid and electricity powered vehicles. Tesar [Tesar, 2010] suggests multi-speed electric hub wheel drives for vehicles. In addition to independent drives for each wheel, active all-wheel steering, camber and active suspension provide full traction control. The philosophy at the Robotics Research Group at UT Austin has been to consider vehicles as robotic systems with individual control of forces at all wheels at all times. In its most general form, this means 4N actuators for an N-wheeled vehicle and best utilization of these actuator resources for given wheel/surface traction conditions to meet the desired operational criteria. Operational criteria include vehicle velocity, yaw, roll, bounce, lateral slip, tire spin etc. As the generality of the vehicle operation expands, to enable greater performance and task versatility, real-time knowledge of vehicle’s environment and its operating conditions is desired. This approach of intelligent vehicle control necessitates deployment of multiple sensors to gather real-time data and get better awareness about the system and its environment.

4.1 SENSORS FOR VEHICLES

Sensors for engine and battery cell system for electric vehicles are already in place up to some level. Sensors for battery cells measure mechanical strain, heat/temperature inside the battery, chemical composition of the electrolyte and output voltage/amperage. These sensors help in maintaining power generation efficiency in the sweet spot of operation, monitor battery charge/discharge levels and keep check on motor current draw due to load.

It is now required to deploy sensors in the sub-system which utilizes the generated power to produce mechanical energy and vehicle motion – namely sensors for actuators, sensors to measure wheel output, sensors in brake system, and sensors to evaluate wheel-terrain interface. The idea is to develop a full sensor suite to obtain as much data on the vehicle's operational state and operating conditions as possible to inform all decision criteria to maximize performance, efficiency and safety [Tesar, 2012].

The following sensors are recommended for intelligent vehicle operation.

Power Utilization (Actuator/Wheel/Brake)	Internal Actuator Sensors Wheel Output Sensors • Wheel Angular Position Rotation, Steering, Camber angles • Wheel Rotational Speed (ABS Sensor) • Wheel Torque Wheel Load Sensor (6 axis) Brake Pad Wear Sensor Brake/Acceleration/Clutch Pedal Force Sensor
Vehicle Platform Sensor	Global Positioning System Inertial Sensors (IMU) • Accelerometer • Gyroscope • Magnetometer Inclination Sensor/Gravitometer Suspension Spring Deflection Look Ahead Sensor (Terrain Evaluation)
Wheel Terrain Interface	Terrain constituents (Ice, Snow, Gravel, Sand, Mud, Water, Asphalt, Concrete etc.) Terrain Compaction Wheel Sinkage • Machine Vision • Ground Penetrating Radar Tire Condition Sensors • Tire Pressure (TPMS) • Temperature • Tire Deflection • Slip/Slip Angle

4.1.1 Actuator Internal Sensors

The modern vehicles will have independent drive wheels powered by intelligent electro-mechanical actuators. To maximize the vehicle performance under a variety of operating conditions, it is important to have real-time knowledge of the driving actuator's operational characteristics and ability to re-configure it on-the-fly to adapt to different conditions and vehicle performance requirements. A multi-sensor architecture for intelligent operation of electro-mechanical actuators has been presented. An actuator is recommended to be equipped with the following sensors [Krishnamoorthy and Tesar, 2005].

1. Position Sensor
2. Angular Velocity Sensor
3. Acceleration Sensor
4. Torque Sensor
5. Temperature Sensor
6. Microphone
7. Vibration Sensor
8. Magnetic Flux Density Sensor
9. Current Sensor (individual actuator)
10. Voltage Sensor (individual actuator)

Figure 5-1 shows location of these sensors inside an actuator. These sensors provide a complete knowledge about an actuator's operating conditions and enable intelligent control of the actuator to respond to unstructured environments and meet performance requirements. Multiple sensors enable fault tolerance, should one sensor fail, its data can be inferred by data from remaining sensors to prevent added sensor from becoming a single point of failure for the actuator.

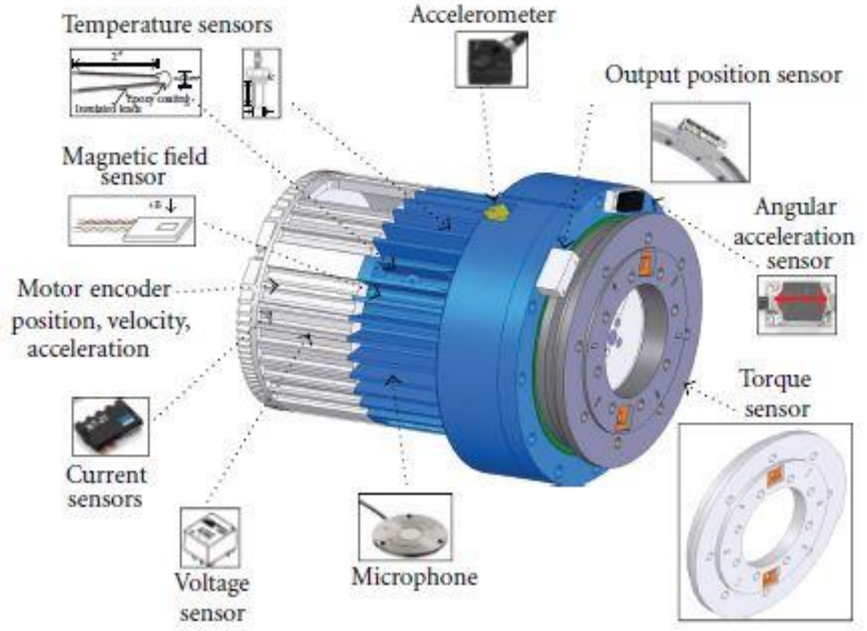


Figure 4-1: Actuator sensors [Krishnamoorthy and Tesar, 2005]

4.1.2 Wheel Speed Sensor

A wheel speed sensor is used to measure the rotational speed of a vehicle’s wheel. A wheel speed sensor is a hub-mounted sensor and typically uses a toothed wheel on the axle drive shaft. Variable reluctance wheel speed sensors use a magnet and a coil of wire (magnet pickup) to generate an analog (alternating) signal. The voltage level is dependent upon the rotational speed of the wheel. A Hall effect wheel speed sensor uses a toothed wheel and generates a square wave signal with frequency proportional to the speed of the wheel. Hall effect sensors need excitation power.

Wheel speed sensors are used in almost all modern vehicles now as a part of the Anti-Lock Braking System (ABS). In ABS, four speed sensors monitor the wheel speeds and check for possible wheel lockups and uncontrolled skidding (one wheel rotating significantly slower or faster than other wheels). The brake hydraulic valves are actuated to reduce or increase the pressure controlling the braking force on the affected wheel.

The ABS is proven to be extremely useful improving vehicle control and decreasing stopping distances on dry and slippery surfaces. The proposed use of wheel speed sensor is not only during braking but it can be used continuously to evaluate the wheel-surface interaction, especially in off-road conditions. Wheel rotational speed is used to calculate the linear speed of the surface contact point or contact patch ($R\omega$). The vehicle ground speed and the wheel contact point linear speed gives data to compute wheel slip – an important parameter in traction control.

Active Wheel Speed Sensor

Producer: Continental

Measurands:

- Measurement of rotational speeds, Air gap measurement

Hardware Attributes:

- Small installation space - the functional components, including the AMR bridge, ASIC and magnet are integrated into a housing 3.2 mm in size
- High resistance to extreme temperatures, from -40°C to +150°C
- Low Operating Voltage (< 5V)
- Enhanced resistance to thermo-mechanical strain

Sensing Attributes:

- Wheel speed is measured using the anisotropic magnetoresistance (AMR) effect.
- Dependable functionality with large air gaps (up to 4.5 mm between sensor and encoder)

Data Processing Attributes:

- Internal signal monitoring

Data Transmission Attributes:

- Standard VDA (German Automotive Standard) data protocol
- Other protocols may be possible

Cost: <10$

http://www.conti-online.com/www/automotive_de_en/themes/passenger_cars/chassis_safety/passive_safety_sensorics/speed_sensors/wheel_speed_sensors_en.html

Wheel Speed Sensor Dephi

Producer: Dephi (SS10308 and other similar parts)

Measurands:

- Measurement of angular speeds and position of the wheel

Hardware Attributes:

- 2.7 x 1.4 x 3.2 inches in size
- 1 pound by weight
- Not impacted by temperature changes and provide robust, long-lasting sensor protection.

Sensing Attributes:

- Hall Effect or magneto resistive (MR) principles for speed and position measurement

Data Processing Attributes:

- Designed digital output for maximum signal to noise ratio.

Data Transmission Attributes:

- Wheel speed signals are transmitted via cables to ABS or ESP control of the vehicle

Cost: $10

Wheel Speed Sensor

Producer: Rexroth, Bosch Group

Measurands:
- Speed measurement

Hardware Attributes:
- Plastic/stainless steel housing material
- Operating temperature -40°C to +125°C in sensor zone and -40°C to +115°C in cable zone
- 12/24 VDC nominal voltage. 6mA nominal consumption
- Approx. 100 grams

Sensing Attributes:
- Hall Effect based non-contact speed sensor. The gear wheel must be a magnetic conductor.
- Two phase-shifted square-wave signals proportional to the speed. Push-pull outputs: Imax = ± 25 mA

Data Processing Attributes:
- Not Available. Possibly none. Provides digital square wave signals

Data Transmission Attributes:
- None

Cost: Expected: $10-$15

http://www.boschrexroth-us.com/country_units/america/united_states/sub_websites/brus_brh_m/en/products_mobile_hydraulics/7_mobile_electronics/a_downloads/re95133_2010-11.pdf

WABCO ABS Wheel Speed Sensor

Producer: MERITOR WABCO

Hardware Attributes:

- Sensor length 65 mm. Cable length options available
- Straight sensor/right angle sensor options
- Sensor clip, sensor bushing

Sensing Attributes:

- Sensor placed over pole wheel teeth with gap less than 0.5 mm
- Output voltage from the sensor is AC (sinusoidal pattern)
- Wheel speed proportional to the frequency of the signal
-

Data Processing Attributes:

- Fault identification possible by ECU

Data Transmission Attributes:

- Wheel speed signals are transmitted via cables to ABS or ESP control of the vehicle

Cost: $10-$20

http://www.meritorwabco.com/MeritorWABCO_document/tp06109.pdf
http://inform.wabco-auto.com/intl/pdf/600/002/000/600_000.pdf

4.1.3 Wheel Torque Sensor

Wheel torque sensor measures torque applied to the wheel or the reaction torque on the wheel. The wheel torque data can be of great interest during off-road driving, braking and coast down. It can give an idea about the required (or actual) energy the vehicle/actuator has to provide to overcome the tire rolling resistance. In Section 4.1.1, the drive actuator is also recommended to be equipped with a torque sensor. The difference between the motor output torque and the wheel torque gives an estimate of driveline resistance and mechanical efficiency. Wheel torque sensors are used during vehicle dynamic testing. It is now suggested to use them during the normal vehicle operation and get real-time torque data from each wheel. Wheel torque is one of the primary input parameters in traction control. Real-time wheel torque feedback is essential for intelligent control of the vehicle based on operating conditions (minimize wheel slippage for higher efficiency).

Wheel torque sensors are typically rotating strain gages on an adapter plate mounted to the wheel rim or bolted to the brake drum or spindle of a car. Temperature compensation is provided in most commercial sensors. A careful design can provide immunity to radial and cornering loads and reduce vulnerability to impact load from wheel terrain interaction. Electrical signals are transmitted either through slip rings or via non-contact rotary transformer. Slip rings are more prone to wear due to friction contact and are subject to intermittent connections and limitations on the rotational speed. Some sensors also provide non-contact telemetry signal transmission to the data acquisition instrument inside the vehicle.

Wheel Torque Sensor


Producer: S. Himmelstein and Company (Product series MCRT® 27000T)

Measurands:

- Non-contact wheel torque meters. Measure wheel torque and speed during driving and braking

Hardware Attributes:

- Waterproof, Corrosion Resistant Construction
- Extraordinary Immunity to Extraneous Loads and Temperature Gradients
- Operating temperature range -25 to +185 F. Compensated range: +75 to +175 F.
- Easy installation. Variety of options available in operating range of the vehicle.

Sensing Attributes:

- Rotary transformers provide non-contact signal coupling to the rotating strain gage bridge
- Optional speed sensor and integrated encoders

Data Processing Attributes:

- Convert raw strain gage data into torque and compute wheel power
- Inbuilt temperature compensation
- Elimination of internally generated shunting error and noise from slip-ring/brush debris

Data Transmission Attributes:

- 4 mV/V output and enhanced impunity to electrical noise.
- ±5 Volt DC Analog Output option available

http://www.himmelstein.com/images/product-datasheets/fe9bcd556650B7800.pdf

Wheel Torque Sensor

Producer: Sensor Development Inc. (90360 Series)

Measurands:
- Measures torque, speed, and temperature of tire/brake systems

Hardware Attributes:
- High extraneous load carrying capabilities.
- Operating temperature range -100 to +500° C
- Vehicle adapter plates with minimal centerline offset (no rim modifications).

Sensing Attributes:
- Typical full scale loads of 7,000in-lbs to 60,000inlbs
- Maximum speed 1200 rpm
- Sensor signal sample rate 950 Hz

Data Processing Attributes:
- Sensor low pass filter - 300Hz, 4-pole Butterworth type

Data Transmission Attributes:
- Non-contact digital FM telemetry to transmit and process signals.
- All output signals are conditioned to a high level analog output for torque, speed, and temperature (2 temp channels). Analog output (receiver) 0 to +/- 5V
- RS-232 serial output (torque only).
- 9V Battery powered transmitter.

http://www.sendev.com/products-and-services/vehicle-test-sensors/braking-force/wheel-torque-sensor/

Wheel Torque Sensor

Producer/Product: Honeywell (Model 1246)

Measurands:

- Measure wheel torque and speed during driving and braking

Hardware Attributes:

- Operating temperature range -20°F to 200 °F. Compensated range: 70°F to 170 °F.
- Easy installation. Designed to be bolted to the brake drum or spindle of a car or truck in place of the regular wheel. Special custom configurations available

Sensing Attributes:

- Accuracy 0.367%, Non-linearity and hysteresis ±0.25 % of rated output
- Standard capacity ranges of 20K, 30K, and 36K in-lb, others available upon request.
- A dc tachometer or 60-tooth gear and magnetic pickup generator options available

Data Processing Attributes:

- Inbuilt temperature compensation

Data Transmission Attributes:

- A slip ring or rotary transformer assembly is provided to connect the torque sensor to an instrument in the vehicle.
- ±1.5 mV/V nominal output

https://measurementsensors.honeywell.com/ProductDocuments/Torque/Model_1246_Datasheet.pdf

Wheel Torque Transducer Instrumentation Assembly

Producer/Product: Michigan Scientific Corporation (TW Series)

Measurands:

- Measure wheel torque, speed, temperature during driving and braking

Hardware Attributes:

- Rugged, weather-proof stainless steel housing
- Operating temperature range -40°F to 300 °F. Compensated range: 75 °F to 250 °F.
- Integrated weatherproof torque transducer, slip ring, encoder, and amplifier assembly

Sensing Attributes:

- Wheel torque transducer that provides one channel of torque data. Possible resolution of 0.1 lb-ft and 0.2 lb-ft
- High accuracy encoder with outputs of 60, 256, 360, 500 or 512 ppr
- Can accommodate multiple strain gage and thermocouple spinning amplifiers

Data Processing Attributes:

- Inbuilt temperature compensation

Data Transmission Attributes:

- Precision amplifiers on the rotating side of the slip ring to improve signal quality and accuracy.

http://www.michsci.com/Products/transducers/wheel_transducers.htm

4.1.4 Wheel Force Sensor

The multi-axis wheel force sensor is used to measure all dynamic forces and moments on a wheel in real time. The wheel force sensor will provide independent output signals for vertical, lateral and longitudinal load on the wheel as well as camber, steer and torque moments acting on the wheel. Vehicles can be analogous to robotic systems with each wheel corner interpreted as a four degree of freedom robotic arm providing active steering, camber, active suspension and drive torque. In an intelligent vehicle, it is desired to know individual control of forces at all wheels at all times. From this analogy, a wheel load sensor provides useful information about the wheel's interaction with the terrain, quite similar to a force-torque sensor at the end-effector of a robotic arm that measures interaction forces with the environment. The wheel force transducer data can be used in stability control, active suspension, traction improvement (traction torque component) and impact load measurements.

Wheel force transducers are strain gage bridge modules which typically mount between vehicle hub and the wheel rim. The sensing elements rotate with the wheel and slip rings or a non-contact rotary transformer is used to transmit signals to a stationary signal conditioning unit. The forces are required with reference to a coordinate system fixed to the vehicle. The rotating electronics package also measures angular position required to transform the force and torque vectors into a non-rotating frame of reference (vehicle's coordinate frame). The six components of the total wheel load are structurally decoupled to provide independent outputs. Wheel force transducers are used in vehicle testing and for road load measurement. It is now recommended to use them on all wheels at all times for intelligent vehicle control.

Wheel force and torque transducers primarily use strain gage bridges to measure torques and forces acting on the wheel. Strain gages are low cost sensing elements but proprietary hardware, signal conditioning, and communication and data acquisition units make all current commercial wheel torque transducers too expensive for wide use. There is a pressing need to standardize these sensors and make a unifying open platform to connect analog and digital sensor output signals to a modular DAQ device on the vehicle. This will drive the sensor cost down and make a multi-sensor system feasible in all complex mechanical systems like vehicles.

Multi Axis Wheel Force Transducer

Producer/Product: PCB Load & Torque Company (Series 5400)

Measurands:

- Six-Axis load on vehicle wheel

Hardware Attributes:

- Rugged one-piece sensor that mounts between the vehicle hub and the wheel rim
- Superior sealing for water and dust ingress protection
- Maximum operating temperature of +302 °F (+150 °C) with superior temperature compensation.
- Easy installation. Robust clamp load and assembly

Sensing Attributes:

- Six axis force moment load cell on wheel. 5 VDC output on each axis
- Non-linearity and hysteresis less than ±0.5 % of full scale output
- Multiple options available with different force/moment sensing range – maximum force ranging from 6600 lbf to 45k lbf and maximum moment ranging from 30k lbf-in to 398 lbf-in

Data Processing Attributes:

- Equipped with on-board signal conditioning and calibration circuitry for each channel of data measurement

Data Transmission Attributes:

- All units can be fitted with either slip ring or telemetry signal transmission

http://www.pcb.com/Linked_Documents/AutomotiveSensors/LT_WFT_Lowres.pdf

MULTI-AXIS WHEEL FORCE SENSOR

Producer/Product: Sensor Development Inc. (77016 Series)

Measurands:

- Measure all dynamic forces and moments on the wheel with reference to the vehicle coordinate system

Hardware Attributes:

- Rugged one-piece sensor that mounts between the vehicle hub and the wheel rim
- Useable temperature -65° F to +250° F

Sensing Attributes:

- 10240Hz/channel sample rate. Encoder 1500 pulse per revolution
- Maximum speed 2500 RPM. Tach generator ±5Vdc

Data Processing Attributes:

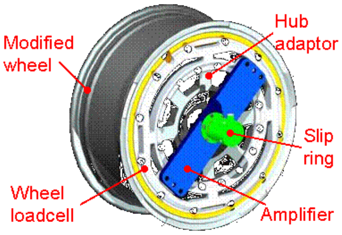
- The rotating electronics package which measures angular position and converts the force and torque vectors into a non-rotating frame of reference (Vehicle's coordinate frame)
- The stationary electronics package which "unpacks" the data from the sensor into individual analog signals. No post processing
- 14 bit A/D convertor resolution

Data Transmission Attributes:

- Digital transmission of signal data. No signal degradation, no slip rings or brush blocks to maintain.

http://sendev.com/catalog/pdf/77016.pdf

Wheel Load Cell



Producer/Product: Sunrise Auto Safety Technology (Specialized in 6 axis load cells)

Measurands:

- Measure three wheel forces and three moments acting on the wheel.

Hardware Attributes:

- The loadcell is completely sealed to provide excellent environment protection, and can be used for on-road measurement on a rainy day.
- Operating temperature range of -40° C to +125° C

Sensing Attributes:

- Measure three wheel forces and three moments. The six components of the total wheel load are structurally decoupled to provide independent outputs
- 150% overload capacity. Non-linearity and hysteresis 1% of full scale.
- The amplifier mounts directly to the loadcell. The amplifier provides high level voltage signal to increase signal-to-noise ratio.

Data Processing Attributes:

- No post processing necessary

Data Transmission Attributes:

- The slip ring transmits the signal from the wheel loadcell to a data acquisition system via a small (Φ4.3mm) flexible cable.

http://www.srisensor.com/prod_wheel.html

Wheel Force Transducers

Producer/Product: Michigan Scientific Corporation (LW Series)

Measurands:

- Measures wheel forces and moments. It provides independent output signals for vertical, lateral, and longitudinal forces as well as camber, steer, and torque moments

Hardware Attributes:

- Rugged, weather-proof - ideal for on-road and off-road measurements in all conditions
- Multiple options available for different vehicle types (passenger cars, light/heavy duty trucks)
- Operating temperature range -40°F to 257 °F.

Sensing Attributes:

- 4 arm strain gage bridges
- Amplifier and slip ring package - Internal X & Z accelerometers.
- High resolution encoder (0.17°) for position & speed measurement
- Maximum non-linearity 1% of full scale and maximum hysteresis 0.5% of full scale.

Data Processing Attributes:

- Amplifier and slip ring package provides signal conditioning & amplification to the transducer strain gage signals
- Transducer interface box performs real-time coordinate transformation and cross-talk compensation

Data Transmission Attributes:

- Transducer interface box - Simultaneous Analog, CAN, & Ethernet signal outputs.

Cost: Not available online.

http://www.michsci.com/Products/transducers/wheel_transducers.htm

4.1.5 Inertial Measurement Unit

An Inertial Measurement Unit (IMU) integrates a multi axis accelerometer, a single or multi axis gyroscope and optionally a magnetometer to track the motion of a rigid body. An IMU on a vehicle platform can give position, orientation, velocity and acceleration of the vehicle. The control input to the vehicle actuators and the wheel terrain interaction directly governs the motion of the vehicle. The IMU data indicating the actual motion of the vehicle can be used (as a feedback) to compute new control input to meet the desired trajectory and required vehicle performance. The IMU data is important in stability control and evaluation of ride quality. IMUs on vehicles can complement the Global Positioning System (GPS) or can work stand-alone when the GPS signals are unavailable.

Low cost MEMS based inertial measurement units are available from a variety of manufacturers. They include a processor chip and a signal conditioning unit which can filter raw data from individual sensors and combine data using sensor fusion techniques to give final position, velocity and acceleration in 6 degrees of freedom. This embedded processing capability reduces computational load on the central computer. Some commercially available inertial measurement units are listed in Section 3.3.3.

4.1.6 Tire Pressure Sensor

Pressure sensor can be used to monitor the tire pressure in real-time. Tires lose air pressure due to leakage and seasonal temperature variations. Most modern vehicles now have a direct tire pressure monitoring system (TPMS). But in the current system tire pressures are gauged infrequently and vehicle operator is given no real-time visual information until the pressure in the tire pressure has become critically low. It is recommended to measure the tire pressure in real-time and use it actively in traction control.

As the generality of vehicles expand, intelligent vehicle operation necessitates active control of tire pressure based on terrain surface characteristics to get maximum available traction. The optimum tire pressure is different for on-road and off-road conditions. For example Dana Corporations' Central Tire Inflation System (CTIS) inflates the tires to 1.6 - 1.8 bar with a 10 -13 percent tread deflection when the vehicle is on smooth road to minimize tire contact with the road surface. When the vehicle travels off-road, the system deflates the tires to 0.6 - 0.8 bar with a 20 - 22 percent tread deflection to increase tire contact with the soil, improving traction and reducing soil compaction [Dana Corp., 2011]. Moreover, real-time tire pressure information can be used in intelligent control of the driving actuator to get optimum performance in given conditions. Active tire pressure control improves tractive performance, increases tread life, reduces vibration and shock loading in off-road conditions, increases fuel economy (3-5% increase), vehicle safety and reduces downtimes associated with tire malfunction which results in increased tire lifetime (increased availability).

Pressure sensors are typically located on each wheel's valve stems (typically screwed) to directly measure the pressure in each tire. Modern MEMS pressure sensors based on capacitive technology also integrate a temperature sensor, accelerometers to detect motion, a microcontroller (MCU), a radio frequency (RF) transmitter in one package.

Tire Pressure Monitoring System

Producer/Product: Duran Manufacturing, LLC (Duran 360 Series)

Measurands:

- Direct measurement of vehicle tire pressure

Hardware Attributes:

- Extremely durable spin-welded sensors include a potting material which encapsulates and stabilizes the internal components and are built with a unique three-piece seal design to maximize valve core depression and minimize leaks
- The system designed to meet stringent SAE standards for vibration, temperature variation, mechanical shock and chemical resistance
- 1.15″Width X 1.30″Height in size, 25 gms weight
- Operating temperature from -40˚F to +257˚F

Sensing Attributes:

- Pressure range 10 to 188 psi
- internal, non-rechargeable & non-replaceable battery
- ± 2 psi accuracy over the range

Data Processing Attributes:

- Standard low pressure warnings are activated at 12.5% and 25% below the programmed baseline tire pressure
- A patent-pending FastLeak™ alarm is triggered with a 2.8psi drop in less than 12 seconds
- A high temperature alarm goes off when the temperature of at 248˚ F

Data Transmission Attributes:

- Wireless (screw on to the valve stem to activate RF signal and transmit data)

Cost: low cost – 10-20$

http://www.doranmfg.com/tirepressuremonitorproducts.htm

Tire Pressure Monitoring System

Producer/Product: Freescale Semiconductors (MPXY83x0 TPMS)

Measurands:

- Direct measurement of vehicle tire pressure, temperature, acceleration in two directions

Hardware Attributes:

- Full integration of a pressure sensor, an 8-bit S08 microcontroller (MCU), a radio frequency(RF) transmitter and a 2-axis accelerometer with X and Z axis in one package
- Temperature range -40ºC to +125ºC
- Complies with the U.S. Federal Motor Vehicle Safety Standard (FMVSS) 138

Sensing Attributes:

- Capacitive sensor technology. Pressure and temperature sensor
- Pressure range min 100 kPa max 450 kPa to 1500 kPa
- ± 7 kPa to ± 20 kPa accuracy over the range

Data Processing Attributes:

- Fully integrated device in single package – Customizable and programmable
- 8-bit MCU with 512B RAM and 16 KB flash
- Over-temperature shutdown
- Supply voltage measurement

Data Transmission Attributes:

- Integrated 315/434 MHz PLL-based RF transmitter
- Multiple baud rate and modulation scheme

Cost: low cost - $5 to $10

http://www.freescale.com/webapp/sps/site/prod_summary.jsp?code=MPXY8300

http://www.freescale.com/files/sensors/doc/fact_sheet/MPXY8300TPMSFS.pdf

4.1.7 Tire Deflection/Deformation Sensor

When a tire tread comes in contact with the road surface, the tread element in the contact patch remains stationary with respect to the surface (pure rolling). The lateral motion of the tire results in deformation of the tread element. As the tread element moves through the contact patch, it is deflected further from the wheel mid-plane. This results in slip angle – the angle between the rolling wheel's true direction of travel and the wheel's mid-plane (direction towards which wheel is pointing). The amount of tire deformation is used to compute slip angle and friction coefficient between the tire and road surface. Real-time information about slip angle, slip ratio, tire forces and tire road friction coefficient can be used in intelligent vehicle control to significantly improve traction and vehicle performance.

The tire deformation sensor can measure sidewall and tread deformations in radial, lateral and tangential directions. An "intelligent tire" will be equipped with a variety of sensors to monitor quantities such as air pressure, strain, temperature, wheel load, tread wear and acceleration to improve vehicle control and safety. Matsuzaki [Matsuzaki and Todoroki, 2008] reviews and proposes sensors for wireless monitoring of tire parameters and their active use in vehicle control. For direct strain monitoring (deformation/deflection sensing), a thin strain gage film (piezo or capacitive-resistive) is commonly attached to the inner surface of the tire. Surface acoustic wave (SAW) sensors have also been proposed for "intelligent tires" to monitor the deformation during road contact [Zhang et al., 2004]. The Darmstadt tire sensor [Breuer et al., 1999] measures tread element deformation in all three (radial, lateral and tangential) directions using a magnet and four hall sensors in arranged in a cross pattern. A non-contact method for sensing tire contact patch deformation using a machine vision system and speckled image tracking algorithm is also proposed [Green et al., 2011] but this method requires an imaging system (camera) placed inside the car which may be infeasible. Moreover, the image processing algorithm can be computationally more demanding than direct sensing and signal conditioning using strain monitoring sensors.

Piezo Sensor – Piezo Film Elements

Producer/Product: Measurement Specialties, Inc (DT Series)

Measurands:

- Strain/deformation measurement. Sensing direct contact force. (Multi-purpose use – vibration sensing, impact sensing, deformation sensing etc.)

Hardware Attributes:

- The piezo film element is laminate to a sheet of polyester
- Unshielded or shielded option available. If shielding is required, the sensor can be enclosed in a proper environment.
- Varying sizes available. Eg. 20 mm × 3 mm× 110 µm
- Operating temperature: 0°C to +70°C

Sensing Attributes:

- The piezo film produces a useable electrical signal output when forces are applied to the sensing area
- Output Voltage: 10 mV-100V depending on Force and Circuit Impedance
- Minimum impedance: 1 MΩ. Preferred impedance: 10 MΩ and higher

Data Processing Attributes:

- Only sensing element. Amplifier and A/D converter circuit board options available

Data Transmission Attributes:

- The dual wire lead attached to the sensor allows a circuit or monitoring device to process the signal

Cost: low cost – $5 to $10

http://www.meas-spec.com/product/t_product.aspx?id=5435
http://www.meas-spec.com/piezo-film-sensors/piezo-film-elements.aspx

4.1.8 Sensing terrain

The current approach for off-road (and on-road) vehicle control pays only little attention to the physical interaction between the wheels (tires) and the terrain surface. Knowledge about terrain properties and soil characteristics can greatly improve wheel traction, odometry and overall vehicle performance (especially efficiency). Sensing capabilities and estimation methods are available now to measure and characterize soil parameters in real-time and actively use the terrain information in vehicle control.

Macroscopic characteristics such as terrain slopes can be determined directly from the vehicle pitch and vehicle roll angles using an inclination sensor or an onboard accelerometer which senses the direction of the gravitational vector. A look down vision sensor can give more information about terrain constituents such as ice, snow, gravel, sand, mud, water, asphalt, concrete etc. and the local surface properties (texture, soil compactness etc.). A vision sensor can also give precise longitudinal and lateral velocity of the vehicle. Deformation and compressibility of the soil can be estimated from a front wheel (for a forward moving vehicle) passing over the soil, and the information can be used for control of the following wheels. Soil compressibility characterizes load carrying capacity of the soil. Reaction of the soil particles to horizontal (lateral) forces represents shear strength of the soil – an important factor providing wheel traction. These soil properties can be roughly inferred in real-time using vision sensors and feedback from wheels while driving. Wheel sinkage is also an important variable in traction control and vehicle-terrain interaction. Sinking of wheels in soft soils inhibits vehicle motion. A low cost camera can be mounted on the vehicle body to "observe" the wheel-terrain interface region. A visual method for estimation of wheel sinkage using a concentric pattern on wheels has been proposed for planetary rovers [Reina et al., 2006]. One of the disadvantages of vision based inference is that this approach is sensitive to lighting variations. A low cost night vision camera or an infrared camera may be better suited. Machine learning techniques such as self-supervised learning are also proposed to classify terrains based in visual appearance and vehicle vibration characteristics due to wheel terrain interaction [Brooks and Iafnemma, 2006].

A look-ahead vision sensor or a laser range finder is used to map global terrain. Terrain range sensors based on laser radar and vision technology are commonly used in planetary rovers and for autonomous navigation. Knowledge about terrain local and global properties is highly desired for future intelligent vehicle navigation and control.

4.2 SENSOR EVALUATION AND SELECTION

Sensor suite evaluation and selection process can be carried out by ranking (on 1 to 10 scale) sensors in each sensing domain based on their **durability (ruggedness), Volume/Weight, power consumption, modularity (ease of integration), embedded processing, cost and technology maturity/commercial availability**. A ranking of 10 represents best possible rank indicating excellent characteristic and a ranking of 1 indicates worst. Table 5-1 represents average ranking of sensors in a particular sensing domain for each characteristic.

Table 5-2 presents a summary of required sensors in the intelligent vehicle system. This table indicates each required or suggested sensing domain, their proposed use in the intelligent vehicle operation, its importance to the vehicle system and the current state of technology or maturity of the sensors in that sensing domain. Importance and maturity is indicated by ranking on 1-10 scale with 10 being the highest.

Table 4-1: Vehicle Sensor Characteristics

Characteristic (Rank) / Sensing Domain	Durability [4]	Power Consumption [2]	Modularity [3]	Embedded Processing [1]	Maturity [4]	Cost [5]	Weighted Ranking
Wheel Position Sensors	9	10	9	8	9	10	9.3
Wheel Speed Sensors (ABS)	10	10	8	10	10	10	9.7
Wheel Torque Sensors	6	8	7	9	7	4	6.2
Wheel Load Sensors	6	8	7	8	6	3	5.6
Inertial Measurement Unit	9	9	9	10	10	9	9.2
Inclination Sensors	9	8	9	10	9	9	8.9
Suspension Spring Sensors	8	9	9	8	8	8	8.2
Look Down Vision	6	8	7	6	7	7	6.8
Look Ahead Vision	5	6	7	7	8	5	6.1
Terrain Sensors/Radar	7	5	6	8	6	3	5.4
Tire Pressure Sensors (TPMS)	10	9	10	10	10	8	9.3
Tire Deflection Sensors	6	9	7	7	6	7	6.7

Table 4-2: Vehicle Sensors Summary

Sensing Domain	Functionality/ Proposed Use	Importance in intelligent vehicle operation	Maturity of sensors	Weighted Ranking
Wheel Speed	Traction Control, Anti-Lock Braking System, Stability Control	10	9	9.7
Angular Position	Traction control, Active Steering, Camber	9	9	9.3
Wheel Torque	Traction Control, Braking System, Safety System	10	6	6.2
Wheel Load	Stability Control, Active Suspension, Active Steering, Stability Control, Terrain Characteristics	8	5	5.6
Brake Pad Wear	Braking System, Safety	10	7	-
Inertial Measurement Unit	Dynamic Stability, Ride Quality and Vehicle Control	10	10	9.2
Suspension Spring Sensor	Suspension Spring Deflection, Vehicle Load, Ride Quality and Stability	8	7	8.2
Look Down Velocity/Vision	Ground Velocity, Lateral velocity, Traction Control (Wheel Slip Calculation)	10	8	6.8
Look Ahead Vision	Terrain Characteristics, Obstacle Avoidance, Safety	7	6	6.1
Terrain Sensors/Radar	Terrain Characteristics for Traction Control	6	4	5.4
Tire Pressure Sensor	Traction Control, Safety (Tire Pressure Measurement System)	10	9	9.3
Tire Deflection	Traction Control, Safety	9	6	6.7

Chapter 5: Sensor Architecture – Issues and Augmentation

The inclusion of sensors in a system provides many advantages as discussed, but it comes with a separate set of issues. These include physical integration of sensors with the existing system, cabling complexities, sensor noise, communication, data management, maintenance, and integration cost.

Once all the sensors for a system are selected and placed, it is vital to address the issue of interfacing the sensors with an embedded controller. The associated wiring complexity is an in important factor in the selection of network architecture for the system. Although wireless sensors are an option, they require additional hardware such as radio frequency transceivers and they can be power hungry. In a multi-sensor system, connecting every sensor individually to the central processor results in large number of cables. Long running cables in a noisy environment makes data susceptible to corruption. It is suggested that similar sensors or sensors on the same sub system connect to a local processor which in-turn connects to the central processor. Local processors handle raw data from sensors and transmit only useful information to the central processor. Such a distributed structure greatly reduces the cabling complexity and offloads computational demands from the central processor. The sensor network architecture (hardware, communication and software) must be modular, provide easy access to data and should require minimum effort for augmenting capabilities.

Even though the sensor technology has advanced significantly over the years, sensors are inherently noisy. There are uncertainties involved in the measurements and sensor data can also degrade over time. An electrically noisy environment can further corrupt the data. It is important to ensure the integrity of the signal along the transmission path. Using shielded cables and twisted pairs for signal transmission, minimizing the number of components along the path, and standardizing connectors and communication interfaces can help alleviate the noise issues. It is desired to get as much accurate and reliable information about the system as possible. Hence real-time sensor data validation and multiple sensor data fusion at a higher level are vital for good system performance. This chapter will discuss some of the most common sensor issues, suggestions on alleviating sensor problems and techniques for sensor data validation and sensor fusion.

5.1 SENSOR ISSUES

A sensor converts the physical quantity that it is measuring into a readable signal. Modern sensors integrated into various systems today generate different kinds of electronic signals. The sensor output can be analog voltage, analog current, frequency modulated or digital signals. Modern control systems require digital information. The data acquisition system converts analog signals into digital information using standard quantization processes. Analog to digital converters are a critical part of a data acquisition system. Prior to digitization, analog signals may be subjected to signal conditioning to make signals more suitable for digitization. Signal conditioning includes filtering, amplification, isolation, linearization, range matching etc. Analog signals are more susceptible to degradation in an electrically noisy environment.

Analog voltage signals can either be referenced to the system ground (grounded source) or it can be floating (not referenced to the system ground). The reference voltages for signals from two independently grounded sources are typically not at the same potential and may exhibit a potential difference from 10 mV to 200 mV. A single-ended output from a sensor is one voltage signal on a single wire referenced to the sensor ground. In most cases, the voltage is proportional to the physical quantity being measured. Hence to assess the correct value of the physical quantity, a data acquisition system should measure the output voltage against a given reference as the sensor ground. Typically the sensor ground is the ground (or negative terminal) of the power supply exciting the sensor. Thus the best practice is to have a common ground for the sensor and the analog measurement module of the data acquisition system. Many other sensors provide differential signals. In this case, two output voltages of similar magnitude with opposite polarity or one varying and one constant voltage provide signal for the sensor. A data acquisition system's analog measurement module takes the difference between two voltages (Hi and Low) to measure the actual voltage difference, which is proportional to the physical quantity. Thus a differential signal provides better common ground noise rejection. But each differential signal requires two analog input channels. Hence single ended inputs are lower in cost (half the number of wires, connectors, and channels used for the same number of output signals) and are preferred where noise is not an issue and there is a common system ground.

5.1.1 Degradation of Signals

Sensor signals can degrade due to internal or external factors. The change in characteristics of the primary sensing element causes sensor output to deviate from the ideal behavior. Various factors (environmental sensitivity, handling, over usage etc.) can affect the sensing element or the physics behind the sensing process. The following listing gives the common types of sensor signal degradation occurring due to internal factors [Brignell and White, 1996].

- ***Bias/Offset:*** Bias or offset refers to a constant difference (offset) between the actual sensor output and the expected/ideal output for the same value of the physical quantity being measured. The sensor output can be visualized as a constant bias being added to the actual value of the physical quantity on every reading. Bias may occur due to one-time overload, improper installation, etc.

- ***Parameter drift:*** Drift refers to slow gradual change in the sensor readings. It can be visualized as a gradually increasing bias being added to the actual value of the physical quantity as the sensor ages. Drift occurs due to factors like overuse, aging, wear, etc.
- ***Cross sensitivity:*** In a perfect world, a sensor would exclusively respond to its target physical measurand. But in the real world all the sensors are sensitive to some extent to variables other than the primary measurand. For example a carbon monoxide gas sensor may respond to hydrogen, ethylene and isobutylene. A part of the sensor output may correspond to the secondary variables. The presence of secondary variables can either increase the sensor output (positive cross sensitivity) or decrease the sensor output (negative cross sensitivity). Most sensors are sensitive to the temperature. Cross sensitivity may result in random variation in the sensor reading. Sensor manufacturers try to maximize the sensitivity to desired variables while minimizing all other responses. Best practice is to operate the sensor in the manufacturer specified range and operating conditions.
- ***Failure:*** Failure refers to the fault mode where the sensor does not provide the desired output in respond to the stimulus [Krishnamoorthy, 2005]. Gradual failure is slow degradation of the sensor signals all the way to complete unresponsiveness. Abrupt failure can occur due to sudden shock or impact and permanent damage to the sensing element. A sudden rise in excitation voltage or current drawn can also result in the sensor failure.

Faulty sensors, when not detected, can give wrong information about the system status which can be disastrous for system performance and safety. Faulty sensors can cause false alarms and affect system diagnosis. Multiple sensors and sensor-process fault detection and management algorithms can help identifying and dealing with a sensor fault with minimum system interruption.

An external factor responsible for sensor signal degradation is noise. Noise is high frequency variations in the measurement signal over its true value. Signal to Noise Ratio (SNR) is a measure of noise level in the signal. It is expressed in decibels as the ratio of signal power to the noise power. Power is proportional to the square of the amplitude. The goal is to have a high SNR, reduce the noise component and maximize the signal. Noise could be added to the signal at different levels. It can originate from the sensing process itself, can be picked up during the signal transmission (electrical noise through EMI in cables), can add at the connection to the measurement device, or during sampling and quantization process.

5.1.2 Causes of Noise

To reduce the noise level it is important to understand the sources of noise. Noise can be added at the sensor itself or during transmission of the sensor signal. Noise generated due to sensor components and interfacing circuits is called internal noise. For example, pink noise or 1/f noise is due to invariable slow fluctuation of the properties of the materials inside sensors such as fluctuating defect configurations in metal, fluctuating trap density and trap location in semiconductors etc. The power spectral density of pink noise is inversely proportional to the frequency (1/f). Whereas white noise is a random signal with flat power spectral density; i.e. it contains equal power for any frequency band. In electronics, the white noise component becomes stronger than pink noise above a threshold (corner) frequency. External noise is added in communication wiring during transmission of the sensor signal. The following are some common sources of noise and their characteristics.

- ***Electrostatic and Magnetic Noise:*** Electrostatic field due to voltage on an adjacent cable/circuit can cause unintended/parasitic capacitive coupling between the signal line and the adjacent circuitry. This unwanted capacitive coupling cause noise by developing charges on the signal line. Changing magnetic fields or moving signal lines in a magnetic field can induce noise in the signal line through electro-magnetic induction. Cables carrying alternating current such as power lines adjacent to the signal cable are a typical source of electro-magnetic noise. Electro-magnetic interference from power lines are typically at 1x and 2x line frequency (50/60 Hz in the US). The noise level is dependent on the degree of coupling between the source and sensor wiring. In general, the higher the current or closer the sensor circuit to the electrical device, the greater will be the induced noise.
- ***Thermal Noise:*** Random motion of electrons (or charge carriers) inside an electrical conductor induces temperature dependent voltage or current in a conductor. This effect is called Johnson-Nyquist noise or simply Thermal noise. The thermal agitation of electrons is independent of any applied voltage. The RMS voltage produced due to thermal noise in frequency bandwidth Δf (Hertz) is given by the following Johnson noise equation

  $$\boldsymbol{v = \sqrt{4kTR\Delta f}}$$

  Where k is Boltzman's constant (joules per kelvin), R is the resistance and T is the temperature (kelvin). Since the noise depends on temperature, sensitive circuits in potentially hot surroundings are sometimes cooled to reduce the noise level.

- ***Ground Loops:*** Ground loops are the most common types of measurement noise when two system components (say a sensor and the measurement module) are not connected to the same ground. Two isolated grounds can have a non-zero potential difference (10 to 200 mV) causing current to flow between two connected terminals which are supposed to be at the same potential. The potential difference may not be constant, resulting in noisy measurement often adding power line frequency components in the measured signal.
- ***Cable Noise:*** Sensor signals are carried in conductors in an insulated cable. Cable material can sometimes generate electrostatic charge when mechanically stressed (Piezoelectric effect). Friction rubbing between the cable's insulator and conductor can generate a surface charge (Triboelectric effect) which can potentially induce noise. These kinds of cable noises are possible when sensors are installed on a moving system (say a robotic platform) and cables connect to a stationary DAQ. Many times cables are routed through a cable tray and are in close proximity to power lines and other sensor and communication links. Noise can be induced through capacitive or inductive coupling from adjacent cables and circuitry.

  The above mentioned noise sources are induced during the signal transmission. Noise/errors are also induced at the measurement device during acquisition of analog signals and their conversion to digital form.
- ***Aliasing:*** While discretizing, a continuous signal sampling frequency should be carefully chosen to be able to reconstruct all the possible frequency components in the original signal. The Nyquist theorem states that the sampling rate/frequency should be more than twice the highest frequency (Nyquist frequency) component of interest in the signal being captured. Sampling at the rate lower than the Nyquist

frequency results in missing higher frequency components and inducing false lower frequency components in the reconstructed signal.

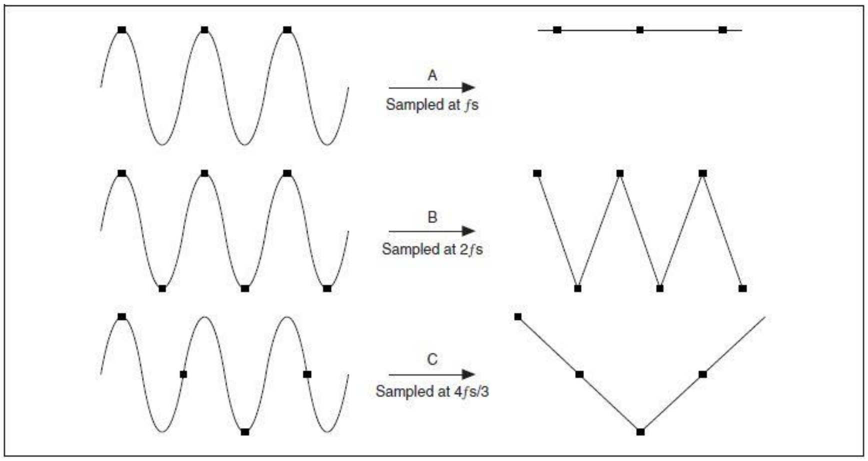


Figure 5-1: Aliasing – undersampling [National Instruments, 2004]

- ***Quantization Error:*** In analog to digital conversion, analog/continuous domain values are mapped to discrete limited values (a many to one mapping). The difference between the actual analog value and the quantized digital value is called quantization error. Quantization error is modeled as stochastic noise. The level of quantization error depends upon the number of discrete output levels an Analog to Digital Converter (ADC) can produce. It also defines the amplitude resolution. For example a 3 bit converter can map analog input values into 2^3 (= 8) discrete values. Greater number of divisions allow accurate mapping of analog signals. It is also important to sample the analog signal at well-defined discrete time intervals. The time resolution is limited by the maximum sampling rate of ADC. The most recent (last) digital value is used until the next signal sampling time. Thus there is no knowledge of the system transition between two consecutive samples. It is commonly assumed to be linear.

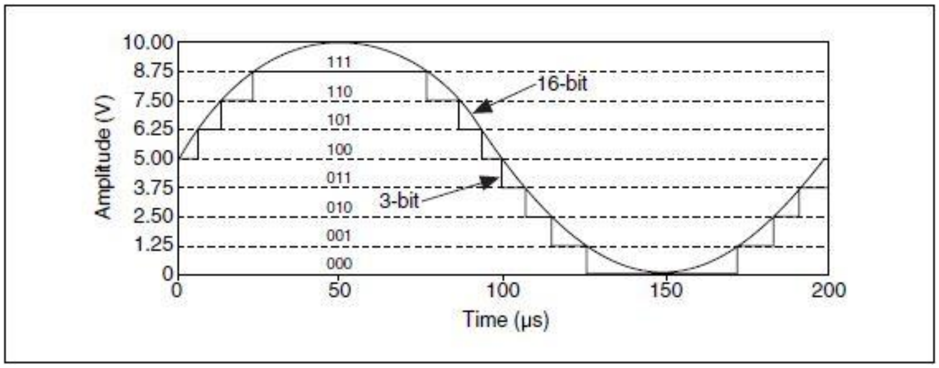
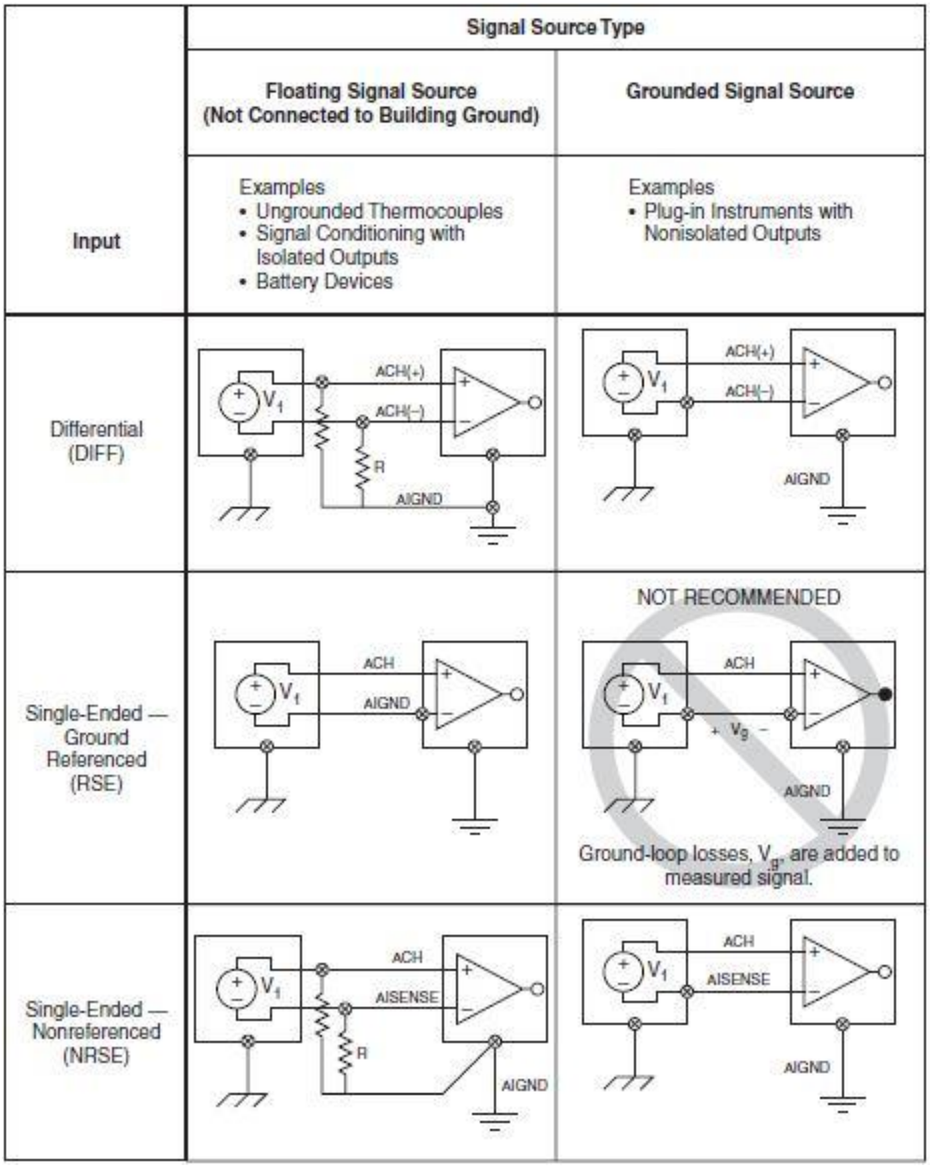


Figure 5-2: Quantization error - ADC resolution [National Instruments, 2004]

5.1.3 Techniques for Noise Reduction

Noise can get added at different levels in the signal flow path. Many techniques are recommended to reduce the noise level. These include using best practices for sensing, signal transmission and measurement to control unwanted noise induction and software techniques to reduce/eliminate noise components from the acquired signal.

- ***Appropriate Measuring Configuration:*** Appropriate type of the sensor signal and measuring configuration can avoid unwanted noise in the measurement signal. The sensor signal can be differential, Referenced Single Ended (RSE) or Non-Referenced Single Ended (NRSE). In the differential configuration, each channel of the signal has a separate negative and positive leads connected to the DAQ module. The DAQ measures potential difference between two leads directly thus rejecting common mode voltage. A differential signal can be measured accurately since the absolute ground potential does not affect the measurement value. A referenced single ended measurement system measures voltage with respect to the ground pin – directly connected to the measurement system’s ground. The sensor ground should be the same as the measurement device’s ground to avoid ground loops. In a non-referenced single ended system, all measurements are made with respect to a single node which is not grounded. Hence, a single channel NRSE system is the same as a single channel differential measurement system. The single-ended configurations are susceptible to ground loops, often showing noise corresponding to the alternating voltage difference between two grounds (source and measurement system).



Input	Signal Source Type	
	Floating Signal Source (Not Connected to Building Ground)	**Grounded Signal Source**
	Examples • Ungrounded Thermocouples • Signal Conditioning with Isolated Outputs • Battery Devices	Examples • Plug-in Instruments with Nonisolated Outputs
Differential (DIFF)		
Single-Ended — Ground Referenced (RSE)		NOT RECOMMENDED Ground-loop losses, V_g, are added to measured signal.
Single-Ended — Nonreferenced (NRSE)		

Figure 5-3: Signal sources and measurement configuration [National Instruments, 2004]

- ***Electromagnetic Noise Reduction:*** Electromagnetic induction due to changing magnetic flux surrounding the signal cable is a common source of noise. A changing magnetic flux can be a result of an alternating current carrying line (say a power line) running adjacent to the signal cable or a moving signal cable cutting the magnetic field lines. Using twisted pair of wires for transmitting the signal dramatically reduces electromagnetic noise. A tightly twisted pair of wires reduces the loop size (flux area). Moreover, two consecutive loops formed due to twisting induce current in opposite directions in each wire thus cancelling them out. Isolation techniques are used to separate signals from each other and from other circuitry in the system. A high voltage carrying signal source can damage the surrounding system circuitry and vice versa, a sensitive signal can pick up noise from the adjacent circuitry if not properly isolated. Common types of amplifiers use magnetic, optical, or capacitive means to couple the signals.
- ***Avoiding Ground Loops:*** Ground loops are arguably the most common source of noise. It is essential to have only one ground reference in the system. If the signal source ground and the DAQ device ground are not the same, the voltage difference between them is not a DC level and typically reflects power line frequency. If for some reason there are multiple references, the two systems should be isolated. Isolators prevent current flow between the two thus removing the potential for ground loops and ensure accurate measurement results.
- ***Minimizing Thermal Noise:*** Thermal noise increases as the temperature and resistance of the measurement circuit increases. Measurement circuits should not be exposed to hot temperatures. Thermal cooling and a path for heat transfer should be provided in the enclosed circuits. Utilizing the same metals at the cable junction,

connectors and avoiding temperature gradients prevent unwanted voltage generation (noise) due to Seeback effect (principal of thermocouples).

- ***Cable Selection:*** The signal transmission phase is most prone to noise induction. Appropriate selection of signal transmission cable is important for reducing noise level. Shielded cables have insulated conductors which are enclosed by a conductive layer (metal foil or conductive polymer shielding). Shielding provides a Faraday cage and reduces noise in signals due to static or non-static electrical fields in the cable environment. It also reduces effect of electro-magnetic induction or electromagnetic radiation from external sources. The shield can be a signal carrier and provide a return path (in coaxial cables) or can be for screening only. Cables with a screening shield are preferred and the shield must be grounded for maximum effectiveness. Twisted pair of wires drastically reduces electromagnetic noise. The cable should be routed such that there is minimum motion or rubbing of cables against each other (or with a surface) to reduce the triboelectric effect. Also in a moving system, all the possible configuration/movements should be reviewed to provide enough slack during operation. The manufacturer specified minimum bend radius should not be exceeded. Cable clamps relieve stress at the terminals and prevent damage during operation. Proper cable routing results in long tern reliability and noise reduction.
- ***Signal Processing Techniques:*** Proper signal acquisition and further processing of raw signals can eliminate the majority of the noise introduced during signal transmission. The measurement frequency should be within the sensor’s bandwidth or dynamic range. The sampling rate must be high enough; 4 to 8 times the highest frequency component expected in the signal being measured to prevent aliasing. The

Nyquist rate is twice the maximum component of frequency in the signal and is the minimum sampling rate required to reconstruct the signal.

Noise filtering can be done in hardware or software. It is desired to filter the noise close to the source and before the signal amplifier to avoid amplification of the noise. Filters are classified based on the frequency (a range of frequency) of the signal it allows to pass through. Signal frequencies outside the band are attenuated. Low pass filters allow frequencies lower than the corner frequency F_c and block higher frequency signals. A high pass filter will allow signal with higher frequency components while rejecting DC and lower frequency signals. Band-pass filters allow frequencies between F_L (lower limit) and F_H (higher limit) and block all other frequency signals. A band-stop filter is opposite of the band pass filter and it allows signals lower than F_L and higher than $F_{H.}$

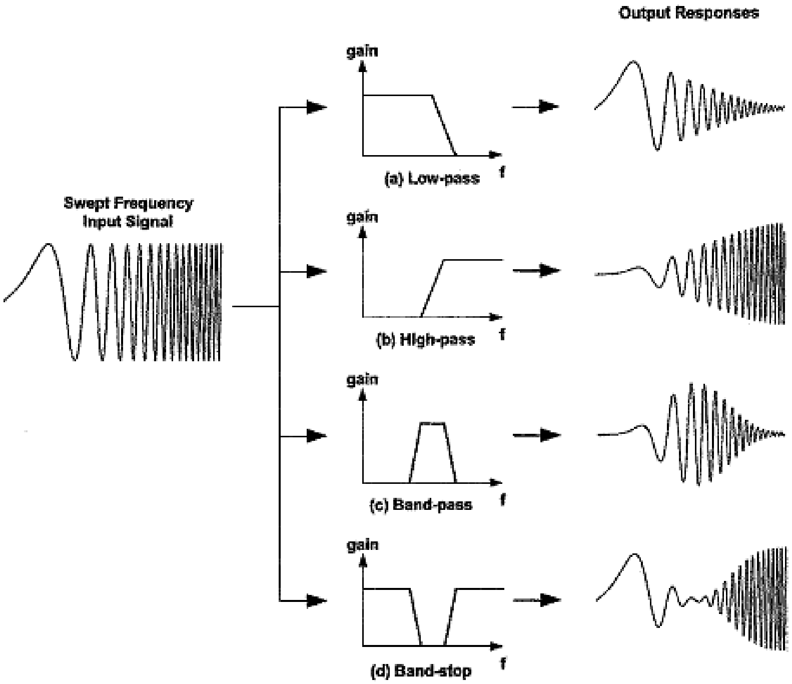


Figure 5-4: Filter types and responses [National Instruments, 2004]

The corner frequency or cut-off frequency is defined as the frequency at which the output starts to attenuate; typically it is at the -3dB of the nominal output. At a 3dB drop, the signal power is approximately halved and the output amplitude is 70.7% attenuated. The filter bandwidth should be as narrow as possible to allow only the desired signal and reject low and high frequency noise. Filters are digitally implemented as difference equations. The Butterworth second order low pass filter is used in many applications. According to Butterworth (a British physicist), it is important for the filter to have uniform sensitivity for allowed frequencies in addition to rejection of the unwanted frequency. The frequency response of a Butterworth filter is maximally flat in the passband and goes down towards zero in the stop band.

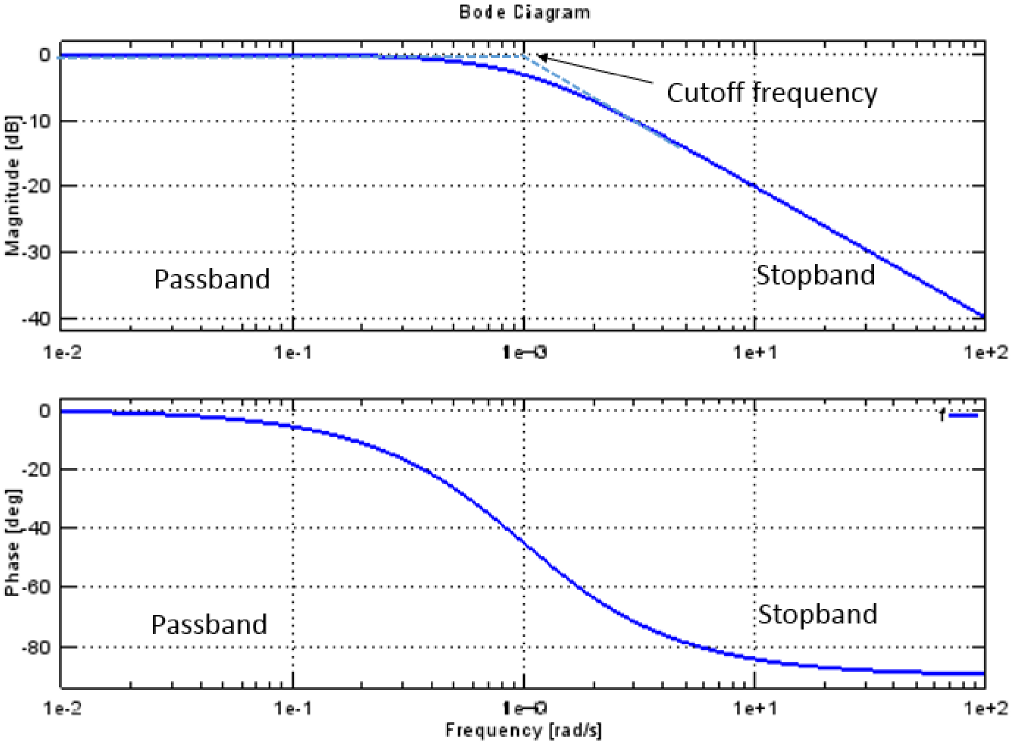


Figure 5-5: Bode plot for first order Butterworth filter

5.2 ADVANCEMENTS IN SENSOR TECHNOLOGY

Traditionally sensors were just transducers which sensed a physical phenomenon and output raw streams of data. It was up to the central processor to do amplification, filtering, bias correction and A/D conversion to interpret signals and obtain meaningful data. To do the same for all the sensors demands significant processing capabilities on the central controller.

An intelligent or ‘smart’ sensor includes necessary computational capability and communication hardware in a single package in addition to the transducer. Raw analog signals are processed and their digital representation is transmitted via standardized communication protocols by the sensor itself. Additionally, some sensors also provide functionalities such as self-testing, compensation for secondary parameters, auto-calibration, fault detection and the possibility to program embedded computational resources. The general architecture for a smart sensor is shown in Figure 5-6.

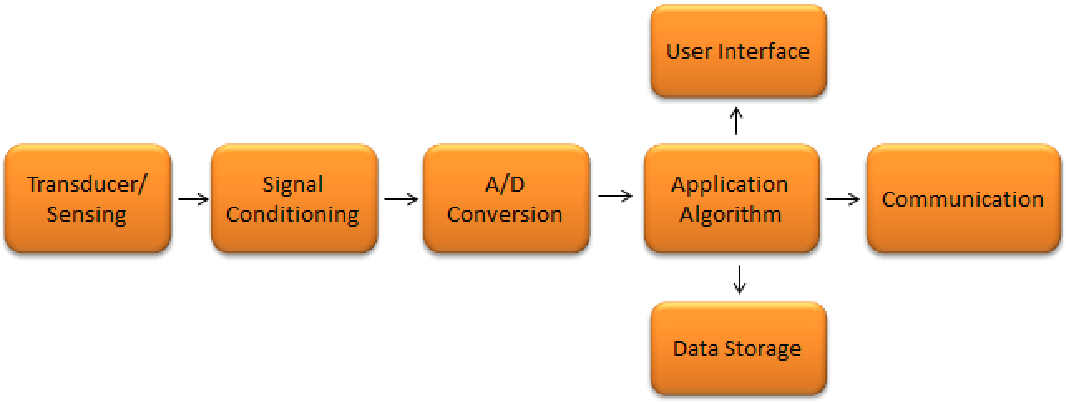


Figure 5-6: General architecture of a smart sensor [Krishnamoorthy, 2005]

Recent advancements in microelectronics and silicon technologies have made production of such ‘smart’ sensors possible and they are beginning to be available commercially at low cost. The smart sensor technology provides numerous advantages:

- Since the signal conditioning and digital transformation of the data occurs within the sensor hardware, sensor information is less susceptible to noise pickup from external environment.
- Data is transmitted over standardized communication protocols enabling plug and play operation and modularity in the system. The central controller software can be independent of the type of sensor used.
- Embedded computational capabilities offer advantages of offloading computational demands on the central processor. It is possible to locally monitor the phenomenon and sensor operation itself to generate alarms. The sensor provides meaningful information rather than raw data thus opening up the communication bandwidth and allowing multiple sensors to be used simultaneously.

5.4 SENSOR DATA VALIDATION

Noise reduction techniques and signal conditioning improve accuracy of the measured data. In many critical applications, just the standard noise reduction methods are not sufficient. It is important to detect abnormal behavior of the sensor itself. Faulty sensor data can result in catastrophic failure of the system. It is essential to validate sensor data and have a ‘confidence value’ associated with each measurement. Sensor data validation is a technique that evaluates measured data and flags uncertain or improbable data to avoid their usage. Sensor data validation techniques use system characteristics, mathematical models and previous data history to predict new value of the measurement. A ‘quality index’ is assigned to the actual measurement based on its closeness/agreement with the predicted value. Reconciliation methods correct inaccurate measurements and provide reconstructed signals for degrading sensors.

Some common validation techniques include checking measured values to lie within the system expected range and flag outlier readings. Maximum change and rate of change of sensor data can also be used to diagnose sensor degradation and failure. For sensors whose characteristics can be captured by a model, estimation techniques such as Kalman filtering can be used to predict an interval within which the sensor measurement would lie. In case of multiple sensors, physical or analytical redundancy can be used to validate sensor data (majority voting scheme) or reconstruct lost data. Complete failure of the sensors is relatively easy to identify, but it is imperative to detect degrading sensor signals and incipient sensor failures to take timely actions. This is done by temporal analysis of the sensor data at regular intervals to check for sensor bias, drift and need for recalibration. Transient system behavior should not be confused with degrading or drift in sensor signals.

It is crucial to distinguish between a faulty sensor and a faulty system. For example, if a sensor reading is 20% higher than the predicted value, the challenge is to determine whether the reading indicates a possible system problem or it is the sensor itself which has drifted out of calibration. This is the principal goal of a sensor process fault management system. Sensor redundancy (physical or analytical) and data from multiple sensors (sensor fusion) can be used identify and distinguish incipient sensor or system faults.

5.5 SENSOR FUSION

The argument for using multiple sensors in all the existing mechanical systems is presented in Chapter 1 and Chapter 2. These sensors would generate huge amount of data that need to be evaluated and integrated. It becomes difficult for a system level controller to analyze data from each individual sensor to make a decision. Moreover, a single sensor may not cover the entire operating regime or it may have limited spatial and temporal coverage given the scope of the entire system. Sensor fusion is a technique of merging/integrating data from two or more sensors to obtain meaningful information (hopefully more accurate and reliable than using individual sensors) about the system state. The information combined from multiple sensors is presented in a simpler and coherent structure to ease in decision making process.

Design and implementation of sensor fusion algorithm is not a trivial task. It includes selection of appropriate sensors, sensor modeling, interpretation of diverse sensor data, and fusion processing. Sensor data can be incomplete, imprecise, and inconsistent with other sensors. Moreover, sensor data can get corrupted during the transmission or sensor itself may degrade over time. Different sensors can have different working principals. The output data may have different units (ex. Position, or velocity or acceleration) and different sampling frequency.

A sensor fusion algorithm should carefully integrate data from multiple sources, taking the above mentioned factors into consideration, to achieve best possible estimate of the actual system state. An inconsiderate fusion approach can result in the final value worse than the best sensor in the system. Outputs from all the sensors to be fused must be converted into a common representation/data structure. Consistency should be checked among data from multiple sensors before integrating them. One method is to compute the Mahalanobis distance between two sensor measurements. It is a unitless measure to evaluate similarities between two sample set and is defined as

$$T = \sqrt{(X_1 - X_2)C^{-1}(X_1 - X_2)}$$

where X_1 and X_2 are two sensor readings and C is co-variance related to two sensors. The Mahalanobis distance differs from Euclidian distance in a sense that it takes into account the correlation between data sets and it is scale-invariant. The lower the distance, the more consistent are the two sensor readings.

In addition to checking consistency among sensors, it is important to assess uncertainty of each sensor reading (‘confidence value’) and propagate the uncertainty in the fusion process. Uncertainty can be characterized by probabilities and belief functions. Uncertainty in sensor data is typically modeled as a Gaussian distribution. Each sensor reading/signal can be assigned a probability from 0 to 1 or it can be viewed as a membership function of a fuzzy set. The center of a symmetric distribution (Gaussian or ellipsoid) is the mean of the measurement and the uncertainty can be indicated by one standard deviation from the mean.

Recent advancements in computational hardware and their availability at low cost have made sensor fusion possible in real-time. Combining data from multiple sensors has significant advantages than using a single sensor. It provides better estimate of the actual physical state of the system. Sensor fusion reduces overall uncertainty of data and increases accuracy of the final output. Multiple sensors can validate each other and provide redundant information increasing robustness and operational reliability of the system in case of a sensor failure. This increases total availability of the system. Fusion algorithm can itself reduce noise in the sensor data as the signal components from multiple sensors are highly correlated whereas noise measurements are random.

One of the side advantages of fusing data from multiple sensors is that it requires sensor data to be represented in a standard format. Data from sensors belonging to the same sub-system can be combined at a local level controller and only useful information is passed on to the system level controller in a standard representation. This allows flexibility in the system with control software becoming more or less independent of the hardware. Sensors based on different working principles and measurement attributes (sampling frequency, output type etc.) can be used without changing the control software. Similarly it is possible to re-design control algorithms without regard to physical sensor types. Thus it improves overall information flow and allows modularity in the system.

Many mathematical techniques exist for fusing data from multiple sensors. It can be a simple averaging of readings obtained from multiple sensors or a probabilistic approach like Bayesian inference or a least square method like Kalman filtering or modern intelligent approaches using fuzzy logic, neural networks or genetic algorithms. Overview of some of the common techniques is presented in the following sections.

5.5.1 Weighted Averaging

In one of the simplest methods, combining data from multiple sensors can just mean taking an average of readings from the sensors. This method would work well if all the sensors have similar accuracy and are operating perfectly. If one of the sensor goes off (say produces bias or drift in the measurements or complete failure) then a simply averaged output can be severely off. A variation of simple averaging is weighted averaging where along with the measurement; quality or confidence in the measurement/reading is also considered in the final estimated value. If Z_i is the reading from the *i*th sensor in an *n* sensor system, the weighted average is given by

$$Z = \sum_i W_i * Z_i \quad where \quad \sum_i W_i = 1$$

Weights can be constant or changing based on the sensor performance and operating regime. In probabilistic terms, sensor output can be viewed as a Gaussian distribution with sensor reading as the mean value and uncertainty in the measurement captured in standard deviation of the distribution. Weight can be inversely proportional to the standard deviation (or directly proportional to the accuracy of the sensor). Sensor data validation algorithm also assigns a confidence value to each sensor reading. The normalized confidence value of each sensor reading can also be chosen as the weight in the fusion process.

5.5.2 Kalman Filtering

Kalman filter is an inference algorithm for linear dynamical system where variable uncertainties have Gaussian distribution. If the sensor can be modeled as a linear system, Kalman filter provides optimal estimates for fused data [Welch and Bishop, 2004]. It is one of the most commonly used data fusion algorithms today – typically in global positioning system, inertial navigation unit etc. due to its small computational requirements and simple recursive estimation of states. It is the least squared error estimator.

There are two main steps in Kalman filter algorithm: time update and measurement update. In the time update, previous system state and control input are used in a linear model to get a priori estimate of the new current state and error covariance. The measurement update step incorporates a new measurement of current state into the priori estimate to obtain an improved posteriori estimate. The Kalman filter algorithm assumes following linear model for the system and measurement

$$\boldsymbol{x_t} = \boldsymbol{A}\boldsymbol{x_{t-1}} + \boldsymbol{B}\boldsymbol{u_{t-1}} + \boldsymbol{w_t}$$

$$\boldsymbol{z_t} = \boldsymbol{H}\boldsymbol{x_t} + \boldsymbol{v_t}$$

The first equation is the system dynamic model where,

$\boldsymbol{x_t}$ is the state vector containing variables of interest for the system at time t

$\boldsymbol{A}$ is the state transition matrix (non-singular)

$\boldsymbol{u_t}$ is the vector containing control inputs

$\boldsymbol{B}$ is the control input matrix applying effect of inputs to the state parameters

$\boldsymbol{w_t}$ is system noise modeled as zero mean multivariate normal distribution with covariance matrix $\boldsymbol{Q}$.

The second equation is sensor model - noisy observation of the system where,

$\boldsymbol{z_t}$ is the vector of measurements at time t

$\boldsymbol{H}$ is the transformation matrix mapping internal states to measurement space

$\boldsymbol{v_t}$ is a vector of measurement noise modeled as zero mean multivariate Gaussian distribution with covariance matrix $\boldsymbol{R}$.

The state transition matrix, control input matrix and measurement transformation matrix are constant in most cases but they can be function of time ($\boldsymbol{A_t}, \boldsymbol{B_t}, \boldsymbol{H_t}$).

The first step is the prediction step to compute an a priori estimate $\boldsymbol{\hat{x}_{t|t-1}}$ of the state $\boldsymbol{x_t}$from previous state $\boldsymbol{\bar{x}_{t-1}}$ and control input $\boldsymbol{u_{t-1}}$

$$\boldsymbol{\hat{x}_{t|t-1} = A\bar{x}_{t-1} + Bu_{t-1}}$$

$$\boldsymbol{P_{t|t-1} = AP_{t-1|t-1}A^T + Q}$$

where $\boldsymbol{P_{t|t-1}}$ is the variance associated with prediction step for yet unknown state $\boldsymbol{\bar{x}_t}$. $\boldsymbol{P_{t-1|t-1}}$ is the final covariance matrix of the previous state ($\boldsymbol{\bar{x}_{t-1}}$).

The second step is the measurement update to compute a posterior (and final) estimate of state $\boldsymbol{\bar{x}_t}$ from the a priori estimate $\boldsymbol{\hat{x}_{t|t-1}}$

$$\boldsymbol{\bar{x}_t = \hat{x}_{t|t-1} + K_t(z_t - H\hat{x}_{t|t-1})}$$

$$\boldsymbol{P_{t|t} = P_{t|t-1} - K_tHP_{t|t-1}}$$

where Kalman gain $\boldsymbol{K_t}$ is given by

$$\boldsymbol{K_t = P_{t|t-1}H^T\left(HP_{t|t-1}H^T + R\right)^{-1}}$$

$\boldsymbol{K_t}$ is Kalman gain and $\boldsymbol{P_{t|t}}$ is the covariance matrix for final state estimation $\boldsymbol{\bar{x}_t}$to be used in the next step. It is a recursive algorithm and the process repeats with t = t+1. The algorithm is initialized with the estimated initial system state $\boldsymbol{\bar{x}_0}$and covariance of the initial estimate$\boldsymbol{P_{0|0}}$. Once the algorithm is initialized, each step is a simple algebraic computation making the Kalman filter well suited for real-time applications.

A simple one dimensional Kalman filter to integrate (fuse) data from two sensors can be demonstrated here. Sensor output can be modeled as a Gaussian pdf (probability density function) with the sensor reading as the mean value (μ) and amount of uncertainty/noise indicated by the standard deviation (σ) or variance (σ^2). If μ_1, σ_1 and μ_2, σ2 are the sensor readings and the standard deviations for two sensors, their Gaussian distributions are given by the following equations

$$y_1(r,\mu_1,\sigma_1) \equiv \frac{1}{\sqrt{2\pi\sigma_1^2}} e^{-\frac{(r-\mu_1)^2}{2\sigma_1^2}}$$

$$y_2(r,\mu_2,\sigma_2) \equiv \frac{1}{\sqrt{2\pi\sigma_2^2}} e^{-\frac{(r-\mu_2)^2}{2\sigma_2^2}}$$

The information from two sensors can be fused by multiplying their Gaussian functions to give an estimate of the actual system state. A key property of the Gaussian function is that the product of two Gaussian functions is another Gaussian function.

$$y_{fused}(r,\mu_1,\sigma_1,\mu_2,\sigma_2) \equiv \frac{1}{\sqrt{2\pi\sigma_1^2}} e^{-\frac{(r-\mu_1)^2}{2\sigma_1^2}} X \frac{1}{\sqrt{2\pi\sigma_2^2}} e^{-\frac{(r-\mu_2)^2}{2\sigma_2^2}}$$

$$= \frac{1}{2\pi\sqrt{\sigma_1^2\sigma_2^2}} e^{-\left(\frac{(r-\mu_1)^2}{2\sigma_1^2}+\frac{(r-\mu_2)^2}{2\sigma_2^2}\right)}$$

Simplifying the above equation, we get

$$y_{fused}(r,\mu_1,\sigma_1,\mu_2,\sigma_2) = \frac{1}{\sqrt{2\pi\sigma_{fused}^2}} e^{-\frac{\left(r-\mu_{fused}\right)^2}{2\sigma_{fused}^2}}$$

where

$$\mu_{fused} = \frac{\mu_1\sigma_2^2 + \mu_2\sigma_1^2}{\sigma_1^2 + \sigma_2^2} = \mu_1 + \frac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2}(\mu_2 - \mu_1)$$

$$\sigma_{fused}^2 = \frac{\sigma_1^2\sigma_2^2}{\sigma_1^2 + \sigma_2^2}$$

Thus the result of the Kalman filter can be expressed as the weighted average where weights are optimally calculated to minimize the squared error.

$$\mu_{fused} = w_1 * \mu_1 + w_2 * \mu_2$$

$$\mu_{fused} = \left[\frac{\sigma_2^2}{\sigma_1^2 + \sigma_2^2}\right] * \mu_1 + \left[\frac{\sigma_1^2}{\sigma_1^2 + \sigma_2^2}\right] * \mu_2$$

$$\frac{1}{\sigma_{fused}^2} = \frac{1}{\sigma_1^2} + \frac{1}{\sigma_2^2}$$

Since the variance of the estimate is less than that of either sensor, it increases the confidence in the value thus obtained.

5.5.3 Bayesian Inference

In Bayesian inference, the probability estimate of the system state (hypothesis) is updated as additional sensor data (evidence) is measured. The information from each sensor is represented as a probability density function or probability values. Bayes' rule is central to computing the posterior probability of the system state given data from multiple sensors and is given by

$$p(H|E) = \frac{p(E|H)\, p(H)}{p(E)}$$

where H stands for any hypothesis, $p(H)$ is the a priori probability of hypothesis H being true (before event E is observed). Here, $p(H|E)$ is the posterior or updated probability of hypothesis H after event E (sensor measurement) is observed. $p(E|H)$ is known as the 'likelihood'. It is the probability of occurrence of event E (getting sensor data) given H is true. It is usually determined based on past experimental results. Thus Bayesian inference provides fused information from multiple sensors or estimated value of the state given measurements from multiple sensors. Priory probabilities are dependent on the sensor physical characteristics and can be determined from sensor specifications (accuracy, sensitivity etc.) and previous experimental results. The left hand side of the equation is the desired estimated value of the state given measurements from multiple sensors. A comprehensive methodology for utilizing data from multiple sensors using Bayesian Networks is discussed in [Krishnamoorthy and Tesar, 2010].

Although the inclusion of sensors in a system provides many advantages, a multi-sensor system has to deal with challenges such as physical integration of sensors with the existing system, cabling complexities, sensor noise, communication, data management, maintenance, and integration cost etc. The chapter discussed best practices to alleviate complexities in a multi-sensor system. Individual sensors cannot be relied upon as each sensor is also a potential single point failure. Sensor fusion techniques are used to combine data from multiple sensors and represent useful information to the controller. A multi-sensor system can take advantage of structured decision making theory [Ashok and Tesar, 2008] and Bayesian network based sensor & process fault management technique [Krishnamoorthy et al., 2011] to improve fault tolerance and overall performance of the system.

Chapter 6: Summary and Future Work

The aim of this report was to establish an argument in favor of using multiple sensors in all the existing and new complex mechanical systems. Recent advancements in sensing technology and availability of computational resources at low cost have made real-time intelligent control practical for complex (non-linear) systems. The emphasis is on modernizing all the existing mechanical systems such as automobiles, railroads, aircrafts, ships, manufacturing and construction equipment, household appliances etc. by equipping them with multiple sensors to get complete knowledge of their operating conditions and to meet required performance criteria under direct human oversight. The following section summarizes work presented in the report.

6.1 REPORT SUMMARY

Chapter 1 provided brief overview of intelligent systems and listed characteristics desired in an intelligent system. An intelligent system is one which has complete knowledge of its operating characteristics at all times (updated in real-time) and it can make on-the-fly decisions to adapt itself to the different conditions or present the best possible options to the human decision maker under specified and ranked criteria. It provides **ability to monitor** both - internal system states and external operating conditions, **criteria based control, fault tolerance**, **condition based maintenance**, and **real-time performance visualization**. A multi-sensor environment is a key to the development of intelligent systems. Chapter 2 discusses benefits of a multi-sensor environment and justifies their need in all the existing complex mechanical systems.

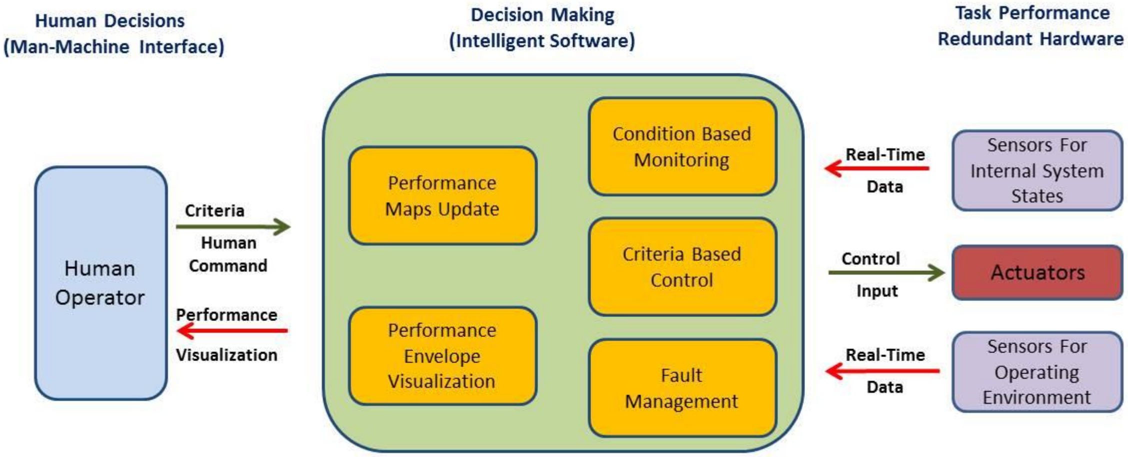


Figure 6-1: Overview of intelligent systems

Krishnamoorthy [Krishnamoorthy and Tesar, 2005] outlines general steps in the process of development of a multi-sensor architecture. These steps include assessment of requirements, translating high level requirements to sensor specifications, evaluation and selection of sensing technologies for the required specifications, followed by sensor placement and system augmentation (intelligent software). The selection of a particular sensor for the system depends upon the functional requirement, and is subject to the constraints on geometry (available space) and suitable sensing technology for a given environment. In general there are some basic characteristics desired in all the sensors. These include **hardware features** such as ruggedness and durability, operating temperature range, ease of integration, sensing method – solid state (no moving parts) or non-contact etc., **measurement attributes** such as accuracy, sensitivity, range, resolution, precision, response time, linearity, hysteresis etc. and **data processing and data transmission attributes** such as embedded processing capabilities, built in self-test features, standardized communication features etc. The sensor attributes and desired characteristics are summarized in Table 6-1.

Table 6-1: Sensor attributes and desired characteristics

Attribute	**Description and desired characteristics**
Hardware Attributes	
Ruggedness and durability	Strong casing, weather proof, able to perform in harsh environments, long life
Operating temperature range	Wide operating temperature range Temperature compensated measurements
Ease of integration	Easy mechanical assembly, Standard electrical connections Plug and Play interfaces. Modular
Portability	Small size, light weight, minimal sub-components
Sensing/Measurement Attributes	
Accuracy	Difference between the measured and the actual values, normally quoted as a fraction of the full scale output
Sensitivity	Ratio of change in the output electrical signal to a small change in the input physical signal; High sensitivity is desirable
Resolution	Minimum detectable signal fluctuation; in general high resolution is preferred
Precision	The degree of repeatability or reproducibility of a measurement
Measurement Range	Maximum and Minimum values of the parameter that can be measured Must match or exceed expected operating range
Response Time or Bandwidth	The response time to instantaneous changes in physical signals, and the decay time for the sensor output to return to original values after a step change in physical signal Bandwidth - How often a reliable reading can be taken

Table 6-1 continued …

Attribute	Description and desired characteristics
Data Processing Attributes	
Built-in Self-Test Feature	Hardware able to detect reliable working or fault .Reduces reliance upon external test setup/algorithm. Low repair cycle times
Embedded Processing	Embedded signal conditioning, amplification, temperature compensation, A/D converters etc. Capable of reliably translating raw data into useful performance information
Data Transmission Attributes	
Noise	Electrical noise not intended for inclusion in the output signal; higher signal to noise ratio is preferred
Sampling Rate	Related to response time and bandwidth. High data transmission rates desired
Communication Protocols	Standard communication protocols, Automatic detection in a network Error checking, Signal amplification, Reduced transmission power desired

Cost, maturity of the technology and commercial availability are also important factors in the selection of a sensor for a particular application. For example a sensor in the prototype or R&D phase may exhibit excellent characteristics mentioned in Table 6-1 but it may not have become a commercial product yet or may be very expensive. Hence it is important to consider benefit to cost ratio while evaluating the sensor options. Nonetheless it is worthwhile to note all the sensors, including the ones still in development phase while creating a multi-sensor environment for intelligent systems. Sensor suite evaluation and selection process can be carried out by ranking (on 1 to 10 scale) sensors based on given specifications. Table 6-2 presents benchmark for ranking based on various sensor characteristics [McFarland and Tesar, 2010]. A normalized rank can be computed by giving weights to each characteristic – for example an additional embedded processor may not be as important if it drives the cost (important factor) up.

Table 6-2: Sensor characteristics ranking benchmarks

Rank Characteristic	10	5	1
Durability /Ruggedness	Industry standard, rugged, weather proof. Demonstrated field use with no reported issues	Likely to perform in most real world-environments, but will require increasing care by the user as conditions become more extreme	Sensor is capable of laboratory use only. Not recommended for outdoor use
Volume/Weight	Appropriate light weight and small size. Does not require extra mounting space	Significantly heavy or may require additional space to mount the sensor	Heavy and bulky. Size prevents effective system operation in a real-world environment
Power Consumption	Self-energizing, No external power supply needed or small excitation voltage	Standard power supply. Low to mid amperage draw	High excitation voltage AC/DC. High amperage draw
Modularity	System is designed for use in a completely open architecture system (hardware and software)	System has some attributes that indicate potential for integration with other sensors	System is completely stand-alone with no method of integrating with other sensors
Embedded Processing:	Sensor output is data meaningful to the operator with filters for noise, and questionable data	Sensor outputs raw data with some accounting for other artifacts that may affect the signal quality	Sensor outputs raw data with no filters for noise or questionable data
Maturity	Commercial-off-the-shelf system available for immediate purchase	Prototype demonstrated, but no commercial product available	Laboratory demonstrations of technology with no working prototype
Cost:	<$100 per unit	<$1,000 per unit	>$10,000 per unit

A multi-sensor architecture for electro-mechanical actuators is discussed in detail by Krishnamoorthy [Krishnamoorthy and Tesar, 2005]. McFarland [McFarland and Tesar, 2010] presents detailed account of body sensors for monitoring condition of soldiers in battle front. In this report, railroad and vehicle systems are suggested to be equipped with multiple sensors for real-time condition monitoring and maximizing system performance.

6.1.1 Summary of multi-sensor environment for railroad cars

Chapter 3 discusses multi-sensor environment for railroad cars. Freight railroads play an important role in a country's economy. They move a large share of the nation's freight, including shipments of oil and gas fueling the country's industrial growth. As a mechanical system trains are remarkably complex system having many components (possible single point failures) and highly non-linear coupled parameters. In the past, limited knowledge of real-time condition of a train's components was the basis for railroad operation. In last few decades, way side sensors have been installed which give information about a train and condition of its components when the train passes in front of a sensor. Modern railroads use a variety of way side sensors such as axle load sensor (Weight-In-Motion), Wheel Impact Load Detector (WILD), hot box and hot wheel detector, brake pads wear sensor, acoustic bearing detectors etc. These way side detectors are expensive and they do not provide real-time information. Additionally wayside sensors have very small amount of time to assess and identify the defects. This results in lack of confidence in the measurements and many inaccurate readings and false alarms. Any alarm requires the train to be stopped and manual assessment of the components by the train crew. An unnecessary stoppage due to a false alarm causes significant train network management problems and costs thousands of dollars to the operator. As the railroad business is expanding, it becomes increasingly essential to monitor and gather data in real-time to make informed decisions to improve safety and efficiency in train operation. It is proposed in this report to develop a full sensor suite made of low cost, small and rugged sensors to deploy on the railroad cars which will give continuous information about the operational state of the car components. The train crew will have real-time operational data displayed graphically on the train computer and alarms can be triggered to warn against potential failures during operation.

In the present research, sensing requirements for railroad cars were evaluated and suitable sensor technology, current state of the art and commercial sensor options are suggested for railroad operators to make informed decisions. Table 6-3 presents a list of onboard sensors suggested for modern railroad cars. These sensors will help in continuous real-time condition assessment of a freight car and its components (axle, bearing, wheels, couplers etc.) during the operation. The real-time data from these sensors will assist in improving performance (efficiency) of a moving train and enable the scheduling of timely maintenance of degrading components, thus reducing downtime and catastrophic failures due to faulty components. Different kinds of sensors can be used to estimate the same physical measurand and evaluate the condition of a component. For example, there is a pressing need in the railroad industry for continuous monitoring of bearings for the purpose of increasing safety and efficiency (predictive maintenance) in the operation. An onboard vibration sensor (accelerometer), a microphone and a temperature sensor – all can be used on the bearing adapter for online bearing defect detection and continuous condition monitoring. This redundancy improves confidence in the sensor data and provides fault tolerance in the sensing system.

Table 6-3: Onboard sensing requirements for railroad cars

Railcar body	Inertial Sensors – Inertial Measurement Unit • Accelerometers • Gyroscope (Yaw, pitch and roll rate) • Tilt Sensing Load Sensor Proximity Sensor (Door lock) Temperature Sensor Pressure Sensor for tanker valve Toxic gas leak sensor Humidity sensors for goods
Car Chassis and Couplers	Vibration sensors Load sensor (strain gauges) • Rail impact sensor • Coupler forces Temperature sensor Vision sensor
Axle, Wheel and Bearings	Vibration sensors/accelerometers Microphone (bearing and wheel defects) Temperature sensor (bearing defects) Shock/impact sensor Proximity sensor (brake piston travel) Brake air pressure sensor Angular velocity sensor (wheel Slip)

The goal was to present to a railroad operator all the essential and supplementary sensing requirements, and potential uses of different sensors on freight cars for monitoring a variety of physical quantities. These sensors need to be low-cost and commercially available to be feasible to deploy on all the railroad cars to improve safety and performance in the railroad operation. Some low-cost sensors may require an external rugged casing to work in the railroad environment for many years. Table 3-10 gives a summary of the sensors discussed in Chapter 3 for railroad cars. The importance rank on a scale of 1 to 10 indicates that sensing domain’s usefulness. A rank of 10 represents a critically useful and is recommended to be deployed on the cars as soon as possible. The maturity column gives a ranking based on the current state of technology for the sensing domain. A rank of 10 indicates that mature, industry proven low cost commercial sensors are available for that sensing domain.

Table 6-4: Summary of sensors proposed for railroad cars

Sensor	**Location/Use**	**Importance/ Critical**	**Maturity**	**Commercial Sensor Options**
Accelerometer	Car Body – Lateral Hunting and Car Dynamics	8	8	MMA8452Q Freescale Semiconductor
				ADXL 345 Analog Devices
	Bearing – Condition Monitoring	10	8	ADXL193 Analog Devices
				MMA81XXEG Freescale
Gyroscope	Car Body – Track Switching	8	7	L3G4200D STMicroelectronics
				IDG500 InvenSense
IMU	Car Body - Navigation	9	8	ADIS16405 Analog Devices MPU 6000/6050 InvenSense
Temperature Sensor	Bearing – Condition Monitoring	10	6	100 Ω Platinum RTD Thermometrics
				Thermocouple Omega
	Cargo/Tank Car	6	8	Vishay NTCLE100E3103JB0 Thermister
				TMP 36 Analog Devices

Table 6-4 continued …

Sensor	Location/Use	Importance/ Critical	Maturity	Commercial Sensor Options
Microphone	Bearing – Condition Monitoring	10	6	4944 Pressure Field Bruel & Kjaer
	Brake – Condition Monitoring	4		ADMP401 Omnidirectional Analog Devices
Proximity Sensor	Brake Cylinder Piston Travel Car Door Lock Status	7	4	GP2Y0A21YK GP2Y0A21YKoF SHARP Infrared Sensor
				VCNL3020 Vishay Semiconductors
				MB Series MaxBotix Ultrasonic Sensors
Pressure Sensor	Tank Car Air Brake System	7	4	SM5420C Board Mounted Silicon Microstructures
				NBP Series Board Mounted Honewell
				AST4530 Submersible American Sensor Technologies
Strain Gages	Coupler Forces Wheel Forces	4	2	CEA Series Vishay Precision Group
				LWK Series Vishay Precision Group

Based on the study of sensors for railroad cars, the following important conclusions are made to develop a multi-sensor architecture for freight trains.

- It is concluded that a vibration sensor, a temperature sensor and a microphone are extremely critical for onboard bearing defect detection and continuous condition monitoring. Mature technologies exist for these sensors and low cost commercial options are available and viable for deployment on railroad car bearings. They may need a rugged casing to survive in the harsh railroad environment.
- Inertial Measurement Units (IMUs) integrate multi-axis accelerometer and gyroscope and are being widely used in industries such as automotive, consumer electronics etc. IMUs are low cost and are highly recommended on railroad cars or every locomotive. They can augment GPS capabilities.
- Several options are available for switch like proximity sensors (Hall effect based) at low cost (~\$1 to 2). But sensors which give continuous distance measurements (Ultrasonic or Infrared) are typically expensive (~ \$25). Hall effect based sensors are suitable for monitoring door lock status.
- Immediate attention is needed for development of low cost devices for force measurement. Strain gage instrumented couplers and wheel sets provide important dynamic information, but strain gages are temperature sensitive and susceptible to degradation over continuous prolonged loading and railroad environments. Current commercial options for force measurements were also found to be too expensive to install on every car.
- With the rise in the number of onboard sensors power consumption, sensor network and communication, and efficient data management are some of the issues that

come into play in the freight train environment. An onboard low-cost energy harvester is required to generate the power. It would energize an onboard battery pack which would provide continuous on-demand power to the network of sensors and data transmission units.

An important consideration for a multi-sensor architecture in railroad cars is connecting sensors to a central processor in each car and relaying information to the locomotive or other remote nodes. The sensor network should be distributed (at least partially) in nature, grouping all the sensors on a sub system and a low power local processing unit dedicated to each sub system. All the sensor sub systems (bearing sensors, brake system sensors, car dynamic response sensors) can have a local processor (a microcontroller) communicating with a central processor (one per car) over the CAN bus (or any other efficient communication protocol). Each car’s central processor can send information to the locomotive about state of the car and its sub components over wireless radio link. Each car in the train consist should have a unique ID in the intra train network (may be GPS location based). The wireless radio link information is received on a locomotive computer which can be running a visualization software to display the state of the critical car components to the operating engineer.

6.1.2 Summary of sensors for vehicle systems

Another case study in the present research is for developing a multi-sensor environment in vehicle systems. Vehicles are arguably one of the most complex and essential machine systems used by human beings on a daily basis. The technology is now moving towards more efficient hybrid and electricity powered vehicles. The Robotics Research Group at UT Austin advocates independent electric hub-wheel drive, active all-wheel steering, camber and active suspension for all modern commercial and battlefield on-road and off-road vehicles [Tesar, 2011]. This will provide potential for intelligent control improving traction and efficiency in the vehicle. Real-time knowledge of vehicle's environment and its operating conditions is desired to enable greater performance and task versatility. This requires deployment of suite of sensors onboard vehicles to obtain as much data on the vehicle's operational state and operating conditions as possible and subsequently make decisions to maximize performance, efficiency and safety.

Similar to railroad cars, sensing requirements for intelligent vehicle operation were evaluated and suitable sensor technology, current state of the art and commercial sensor options are suggested for decision makers. Table 6-5 presents a list of onboard sensors suggested for modern vehicles. The commercial sensors were evaluated based by ranking (on 1 to 10 scale) sensors in each sensing domain with respect to their **durability (ruggedness), volume/weight, power consumption, modularity (ease of integration), embedded processing, cost and technology maturity/commercial availability**. Each characteristic is given a weight based on its importance/need in sensors. Table 6-6 represents average ranking of sensors in a particular sensing domain for each characteristic and a weighted rank for typical sensors in that sensing domain.

Table 6-5: Vehicle system sensing requirements

Power Utilization (Actuator/Wheel/Brake)	Internal Actuator Sensors Wheel Output Sensors • Wheel Angular Position Rotation, Steering, Camber angles • Wheel Rotational Speed (ABS Sensor) • Wheel Torque Wheel Load Sensor (6 axis) Brake Pad Wear Sensor Brake/Acceleration/Clutch Pedal Force Sensor
Vehicle Platform Sensor	Global Positioning System Inertial Sensors (IMU) • Accelerometer • Gyroscope • Magnetometer Inclination Sensor/Gravitometer Suspension Spring Deflection Look Ahead Sensor (Terrain Evaluation)
Wheel Terrain Interface	Terrain Constituents (Ice, Snow, Gravel, Sand, Mud, Water, Asphalt, Concrete etc.) Terrain Compaction Wheel Sinkage • Machine Vision • Ground Penetrating Radar Tire Condition Sensors • Tire Pressure (TPMS) • Temperature • Tire Deflection • Slip/Slip Angle

Table 6-6: Vehicle sensor rankings

Characteristic (Rank) / Sensing Domain	Durability [4]	Power Consumption [2]	Modularity [3]	Embedded Processing [1]	Maturity [4]	Cost [5]	Weighted Ranking
Wheel Position Sensors	9	10	9	8	9	10	9.3
Wheel Speed Sensors (ABS)	10	10	8	10	10	10	9.7
Wheel Torque Sensors	6	8	7	9	7	4	6.2
Wheel Load Sensors	6	8	7	8	6	3	5.6
Inertial Measurement Unit	9	9	9	10	10	9	9.2
Inclination Sensors	9	8	9	10	9	9	8.9
Suspension Spring Sensors	8	9	9	8	8	8	8.2
Look Down Vision	6	8	7	6	7	7	6.8
Look Ahead Vision	5	6	7	7	8	5	6.1
Terrain Sensors/Radar	7	5	6	8	6	3	5.4
Tire Pressure Sensors (TPMS)	10	9	10	10	10	8	9.3
Tire Deflection Sensors	6	9	7	7	6	7	6.7

Table 6-7 summarizes the recommended sensors for intelligent vehicle system. This table indicates each required or suggested sensing domain, their proposed use in the intelligent vehicle operation, its importance in intelligent control of vehicle system and the current state of technology or maturity of the sensors in that sensing domain.

Table 6-7: Summary of recommended vehicle sensors

Sensing Domain	Functionality/ Proposed Use	Importance in intelligent vehicle operation	Maturity of sensors	Weighted Ranking
Wheel Speed	Traction Control, Anti-Lock Braking, Stability Control	10	9	9.7
Angular Position	Traction control, Active Steering, Camber	9	9	9.3
Wheel Torque	Traction Control, Braking System, Safety System	10	6	6.2
Wheel Load	Stability Control, Active Suspension, Active Steering, Terrain Characteristics	8	5	5.6
Brake Pad Wear	Braking System, Safety	10	7	-
Inertial Measurement Unit	Dynamic Stability, Ride Quality and Vehicle Control	10	10	9.2
Suspension Spring Sensor	Suspension Spring Deflection, Vehicle Load, Ride Quality and Stability	8	7	8.2
Look Down Velocity/Vision	Ground Velocity, Lateral velocity, Traction Control (Wheel Slip Calculation)	10	8	6.8
Look Ahead Vision	Terrain Characteristics, Obstacle Avoidance, Safety	7	6	6.1
Terrain Sensors/Radar	Terrain Characteristics for Traction Control	6	4	5.4
Tire Pressure Sensor	Traction Control, Safety (Tire Pressure Monitoring Sys)	10	9	9.3
Tire Deflection	Traction Control, Safety	9	6	6.7

Although the inclusion of sensors in a system provides many advantages, a multi-sensor system has to deal with challenges such as physical integration of sensors with the existing system, cabling complexities, sensor noise, communication, data management, maintenance, and integration cost etc. Chapter 5 of the report addresses these issues in detail and discusses best practices to alleviate complexities in a multi-sensor system. Data validation and sensor fusion techniques are also discussed briefly for the sake of completeness. Individual sensors cannot be relied upon as each sensor is also a potential single point failure. Sensor fusion techniques are used to combine data from multiple sensors and represent useful information to the controller. It is also important to detect abnormal behavior of the sensor itself. Faulty sensor data can result in catastrophic failure of the system. Sensor data validation techniques use system characteristics, mathematical models and previous data history to predict new value of the measurement. Some basic data validation methods and mathematical techniques and algorithms for sensor fusion are described in Chapter 5. A framework was developed for utilizing data from multiple sensors in intelligent mechanical systems [Krishnamoorthy and Tesar, 2010].

6.2 FUTURE RESEARCH

6.2.1 Sensor Development

In this report potential advantages of multi-sensor systems were presented with two detailed case studies – railroad cars (freight trains) and vehicle systems. Sensors for these systems were selected from commercially available options. However there exists a lot of scope for improvements and maturity in sensors for some sensing domains. For example force/torque sensors use strain gages which can be sensitive to weather conditions (especially temperature). Rugged commercial options are available but they seem too expensive to deploy on every system. Further research and development is required for weather resistant, low cross sensitivity sensors. Effort is needed to produce sensors in quantity and drive the cost down for some sensing technologies. Some systems may require development of custom sensors based on constrains on geometry and sensor environment.

The framework for developing a multi-sensor architecture is established at this point. It is now essential to demonstrate the argument and advantages presented in this report with a working prototype of a multi-sensor system. One such feasible demonstration could be of a network of body sensors. Wearable sensors monitor the physical condition of a machine operator in real-time. A wide variety of biofeedback sensors are available commercially which can give information about physiological conditions such as heart rate, skin temperature, perspiration, muscle tone, eye pupil movement, brainwaves (neural signals), respiration etc. It may be infeasible to include all the sensors at once for a system development. The effort can begin with a selected set of technologically mature, high priority sensors (say five to six sensors total), integrating them in a network (for example Body Sensor Network) and acquiring real-time data from these sensors for a selected set of operations. The crucial step would then be to analyze and interpret sensor data, show relationships among data from different sensors, establish statistical correlation, infer the same information from different sensors, and in case of an electro-mechanical system, use the sensor information for intelligent control of the system. This initial effort should focus on demonstrating the feasibility of a multi-sensor intelligent system and should clearly illustrate its advantages to justify further development. This kind of demonstration can take advantage of structured decision making theory [Ashok and Tesar, 2008] and Bayesian network based sensor & process fault management technique [Krishnamoorthy et al., 2011] to prove enhanced performance of complex systems in a multi-sensor environment.

A working prototype demonstrating the concept and benefits of a multi-sensor environment is immediate future goal. More sensors can be added in future to expand upon the idea and update performance maps of the system. In many fields, such as biofeedback sensors, home automation etc. the sensor hardware and software are proprietary and expensive. A unifying open platform is needed for the eventual goal of developing a modular system capable of being reconfigured on-demand to meet task requirements.

6.2.2 Sensor Integration

The first reality of an expanded sensor system is that it must not represent a new set of single point failures (one sensor failure shuts the whole system down). Hence, the sensor data management system must infer lost data from any failed sensor in the network (one can use Bayesian networks for this purpose). This means that the data/network structure must be reconfigurable on demand. Obviously, sensor durability and ruggedness become an important measure in selling the setting up the sensor network. Also the sensor communication networks, data processing/reduction etc. should be even less likely to fail.

As the system application matures, some networks may only require 5 distinct sensors (although there may be duplicate sensors if they are low enough in cost) or a complex system may require 15 distinct sensors. Hence the architecture of the network and the data handling system must also be rapidly reconfigurable (made larger or smaller).

6.2.3 Map Maintenance

All intelligent systems are inherently complex (many operational goals), they are increasingly nonlinear and highly coupled with ever changing criteria for good operation. These criteria are best presented as parametrically based maps (efficiency, force level, temperature, noise, etc.) that can be presented visually to a human operator or to become a way to structure the decision process (moving towards envelopes with sweet spots or danger zones) for directed computational procedures to augment the operator’s ability to make the best decision. Hence, maintenance (updating) of the maps keeps the decision process timely and relevant. This human supervised process is then what is really meant by system intelligence. Updating the maps accounts for changes in the system (wear, material changes, wiring resistance changes, etc.) This updating can also generate lessons learned for archiving and future system design development. None of these objectives could be achieved without a full sensor network generating real-time data to represent the system.

6.2.4 Human Interface

Both the human operator and the system must be “intelligent”. Both must be represented by sensor based maps. The maps for the human are, of course, the most complex and can rapidly change because of changes in the human condition. The human and system maps can be married (formed into combined maps or envelopes). Several decades ago, it was recognized that it is easy to “swamp” the decision capability of an airplane pilot by providing him/her excess and uncoordinated information. The same is true today for the surgeon, the train engineer, the truck driver, mining machine operator etc. wherever high skills or high cost of failure is involved. Here it becomes clear that body sensors/networks will become essential as the larger technology moves forward. This is now becoming obvious for the soldier on patrol in the battlefields. For the train engineer, he/she needs real time data on the train to enhance efficiency, achieve timeliness, and to prevent accidents (derailments). Further the train network supervisor can now more effectively govern/operate a network of trains, reacting to potential human or system failures. Even though this is complex, think of the complexity of the internet, cloud computing and medical records handling. Measures for cost effectiveness, safety, efficiency, etc. all demand intelligence in decision making which starts with accurate operational data for self-awareness and self-regulation which requires distributed sensors which was the principal theme of this report.

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