Future Inspection of Overhead Transmission Lines

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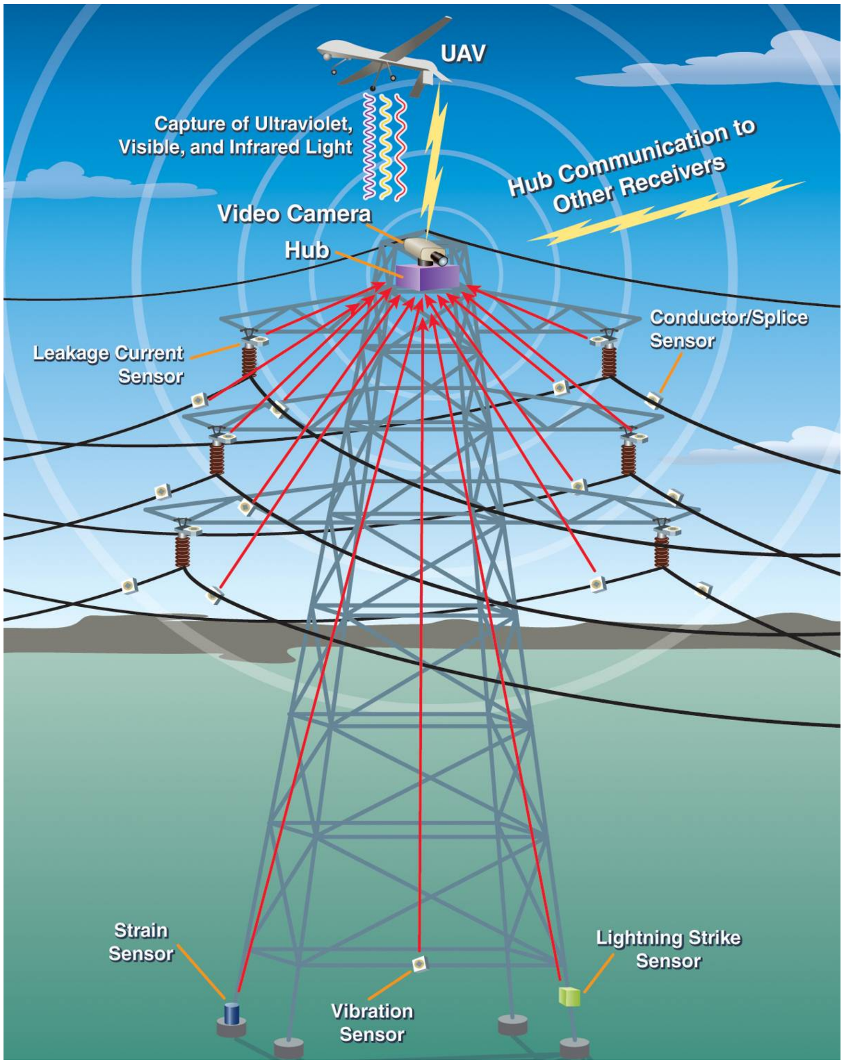

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Future Inspection of Overhead Transmission Lines

1016921

Technical Update, May 2008

EPRI Project Manager
A. Phillips

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Product Description

Results and Findings

This report documents scenarios and technologies that can be applied in the future for the inspection of transmission lines. Scenarios describe the utilization of a range of concepts, including distributed sensors, unmanned airborne vehicles, RF communication, and robotics. An approach to performing demonstration projects using currently available technologies is provided and will be implemented in the following phases of the project.

Challenges and Objectives

Possible visions for the inspection of transmission lines in a multi-decade time frame are provided here. As the requirements for transmission line reliability and availability become more stringent and the availability of qualified personnel is reduced, technology will become a major enabler. This report documents possible technologies and scenarios that may help in meeting these challenges.

Applications, Value, and Use

A demonstration of some of the concepts using some of the currently available technologies will be underway in 2009. This document serves as a roadmap for the demonstration.

EPRI Perspective

This report provides a vision for the future of inspection and assessment of transmission lines and sets the basis for technology development and demonstrations in the future.

Approach

Utility staff familiar with transmission line inspection, experts in sensing and communicating technology, and transmission system researchers collaborated to develop this document.

Keywords

Transmission line
Inspection
Assessment
Future

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1 BACKGROUND

Transmission line components are currently inspected & assessed utilizing field personnel, whether ground based or airborne. EPRI, and others, have in the past, and are currently developing inspection technologies for implementation using traditional manned inspection methods. The consideration for automated/unmanned implementation of inspection technologies is generally not accounted for in developments, as viable approaches for automated inspection are not in place and it is a futuristic thought rather than a present day reality. With the advent of transmission line security issues the pressure/opportunity for automated, unmanned/continuous monitoring on transmission lines is increasing with a nearer term focus. Technology developments in sensors, robotics, unmanned vehicles, satellite and wireless data communications could be leveraged to enable the development of an effective automated inspection system for transmission line/tower monitoring applications.

A meeting was held on May 16, 2007, with EPRI and some of their electric power utility members, in order to kick off this effort.

EPRI provided the following reports for reference:

- Overhead Transmission Inspection and Assessment Guidelines – 2006, 4th Edition (1012310)
- Airborne Inventory and Inspection of Transmission Lines, Airborne Patrol System Advanced Prototype, Technical Progress, November 2000 (1001168)
- Airborne Inventory and Inspection of Transmission Lines, Unmanned Airborne Vehicle (UAV), Final Report, September 2000 (1000712)
- Airborne Inventory and Inspection of Transmission Lines, Avcan System Corporation's Helicopter Patrol System, Final Report, March 2000 (TR-114773)
- Airborne Inventory and Inspection of Transmission Lines, Airborne Patrol System, Final Report, December 1999 (TR-114229)
- Airborne Inventory and Inspection of Transmission Lines, Unmanned Airborne Vehicles (UAV), Final Report, December 1999 (TR-113682)

The objectives and outline of this document are as follows:

1. Document the system concept as agreed upon at the kick off meeting
2. Address candidate technology for the system
3. Address demonstration scenarios for potential near future implementation

2

SYSTEM CONCEPT

A system concept is defined for the instrumentation of electric power utility towers with sensor technology designed to increase the efficiency, reliability, safety, and security of electric power transmission.

The system concept is fueled by a list of sensing needs that was generated at the kickoff meeting and is provided for reference in Figure 2-2. The variety of sensor needs is illustrated in **Figure 2-1**.

It was agreed that the system scope is limited to transmission line applications (i.e., 69 kV and above), not distribution, with the focus on steel lattice and pole structures, not wooden.

It was also agreed that the addition of wiring to interconnect and/or power distributed sensors is not viable because of electromagnetic susceptibility concerns and labor intensive installation. Consequently, sensor concepts will rely on wireless and/or fiber optic technology.

Figure 2-2 and **Figure 2-3** shows some of the high level concepts that are listed below:

- Sensors distributed on transmission structures and/or conductors.
- Sensors that may or may not communicate with "hub" installed on the structure – either wireless or wired.
- Sensor information is collected, stored and analyzed in a "central database" which is part of the utility's current data management system. The data is collected/communicated from the sensors/"hubs" to the "central database" using one of the following methods:
    - Wirelessly back to the "central database" from the individual structure "hub", e.g. RF directly, via satellite or cell phone network.

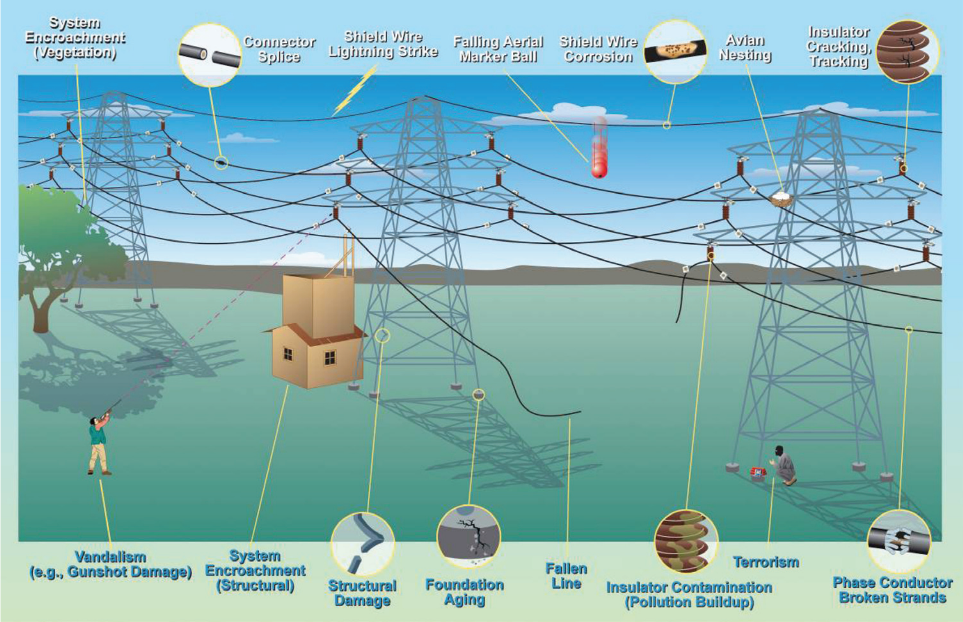

Figure 2-1
Illustration of Sensor Needs for Transmission Lines and Towers

- Collected using a vehicle traveling the length of the line. The data from the collection vehicle is transferred during or after the inspection. The following is a list of possible data collection vehicles:
  - Unmanned Airborne Vehicle (UAV)
  - Manned Aerial Vehicle
  - "Line Crawler" Robot
- If the vehicle data collection approach is utilized:
  - The vehicle may collect the data wirelessly directly from the sensors (possibly excluding the need for a structure "hub").
  - The vehicle may also have sensors aboard recording data during the collection process, (e.g. video, UV, IR, still images).

These concepts are discussed in detail in the following sections.

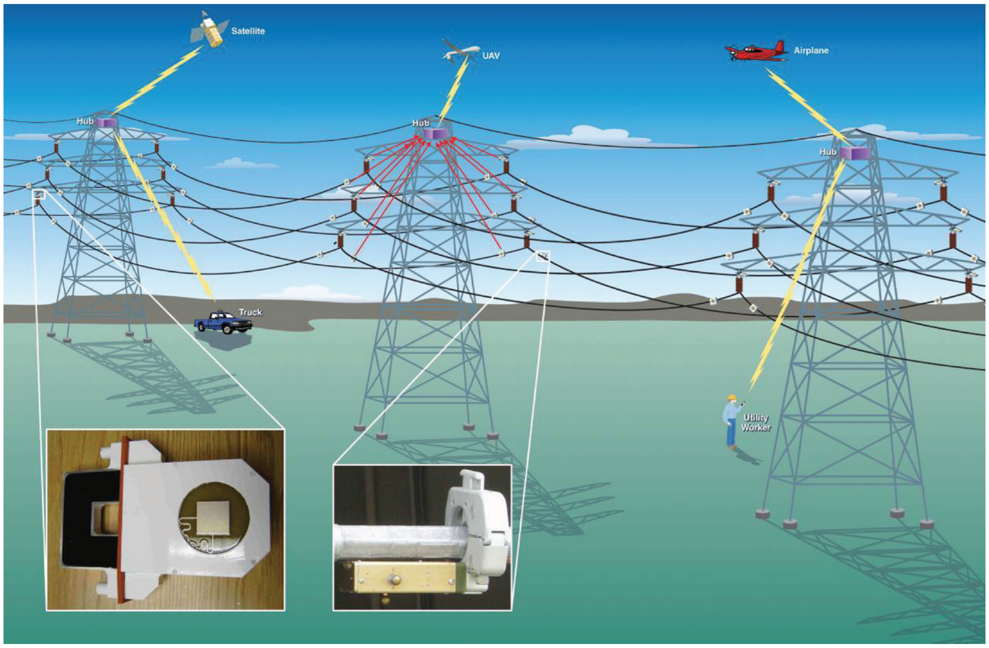

Figure 2-2
Conceptual Sketch Showing Possible Scenarios for Inspecting Transmission Lines of the Future

2.1 System Architecture

The system is comprised of a) sensors that acquire diagnostic data from components of interest and b) communications hubs that collect the sensor data and relay it to a central repository. Sensors may be directly attached to the item being monitored, or may be remotely located such as in the case of a camera. Communications hubs may be mounted on or near towers or may be located on a wide variety of mobile platforms, such as manned airplanes or unmanned line crawlers or UAVs. Sensors and hubs may operate and be polled periodically (e.g., at intervals of minutes, hours, days) or continuously monitored (e.g., a real time alarm) depending on the application. In any case, sensors communicate their results via hubs to a central repository. **Figure 2-4** illustrates the architecture and flow of data.

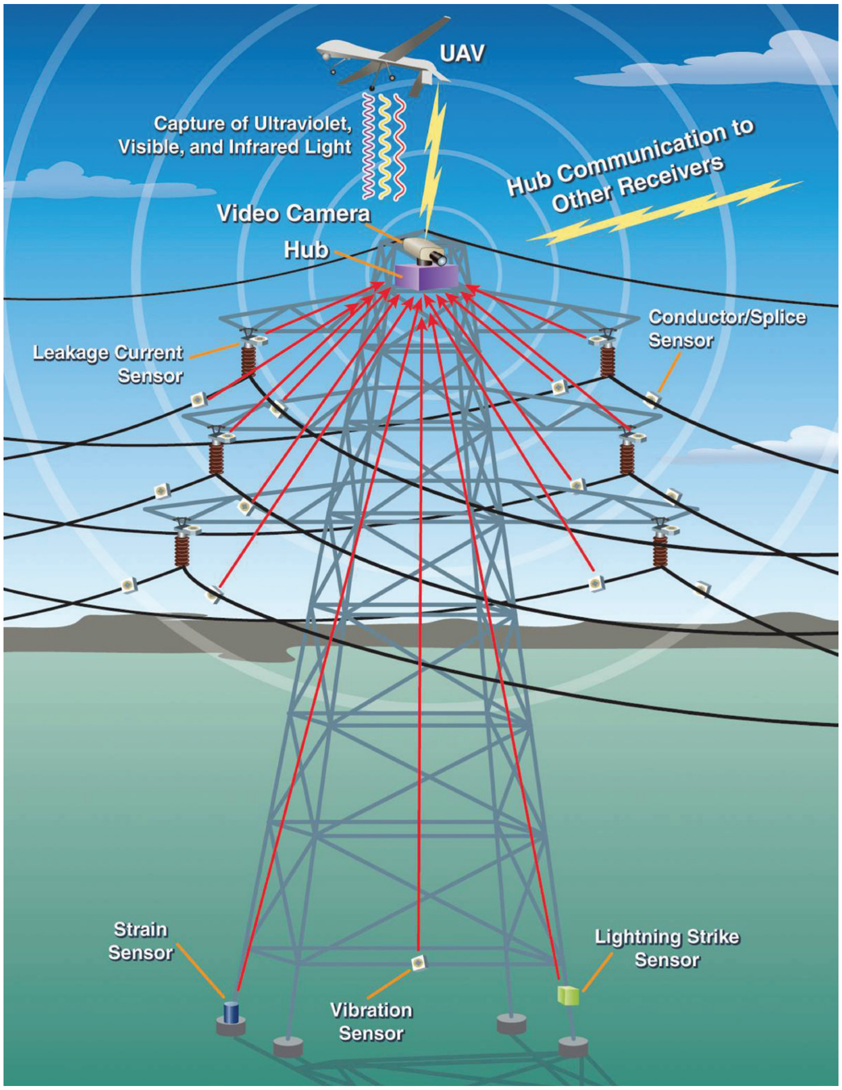

Figure 2-3
Image Showing a Single Structure Illustrating Some of He Concepts

An important feature of the system is flexibility and interoperability with a wide variety of sensor types and communications methods. The information that is required for each sensor reading is:

- Unique sensor ID (across all sensor types)
- Raw data measurement or processed result
- Date and time of the reading
- Sensor type and geo-location

The sensor type and geo-location may be associated with the ID and hard coded in a database at the central repository so that this information doesn't need to be redundantly transmitted through the system for every reading. For remote mobile sensors, the geo-location will need to be communicated so that the system can associate the reading with a particular item (at a known geo-location) or area of interest.

Table 2-1
List of Sensor Needs

	Item	Cause	Result	Update Interval	Probability	Consequence	Sensing Technologies
1	System Tampering	Terrorism	Tower/line down	Real-time	Low	High	Vibration, Acoustic, E-Field, Optical
2	System encroachment	Man-made	Safety hazard, Less reliable	3–12 mo	High	Med	Optical, Satellite, Proximity, Vibration, E-Field
3	System encroachment	Vegetation	Flashover, Fire	3 mo	High	High	Optical, Satellite, LIDAR, Line-of-Sight, Proximity
4	System encroachment	Avian Nesting, Waste	Flashover	6–12 mo	High	High	Optical, Vibration, Leakage Current, Proximity, E-Field
5	Shield Wire	Corrosion	Flashover, Outage	3–6 years	Med	High	Optical, IR Spectroscopy, Eddy Current, MSS
6	Shield Wire	Lightning	Flashover, Outage	1 year	Med	High	Optical, IR Spectroscopy, Eddy Current, MSS, Lightning Detection, Vibration
7	Insulator (Polymer)	Age, Material Failure	Outage	6 years	Med	High	Optical, Vibration, RFI, UV, IR
8	Insulator (Ceramic)	Age, Material Failure	Outage	12 years	Low	High	Optical, Vibration, RFI, UV, IR
9	Insulator	Contamination	Flashover	3 mo	Med	Med	Optical, RFI, UV, IR, Leakage Current
10	Insulator	Gun Shot	Outage	Real-time, 3 mo	Med	High	Optical, Vibration, RFI, UV, IR, Acoustic
11	Phase Conductor	External strands broke	Line Down, Fire	1 year	Low	High	Optical, Vibration, RFI, UV, IR
12	Phase Conductor	Internal strands broke	Line Down, Fire	1 year	Low	High	E-MAT, MSS, Electromagnetic
13	Phase Conductor	Corrosion of steel core	Line Down, Fire	1 year	Low	High	E-MAT, MSS, Electromagnetic, IR Spectroscopy, Optical

Table 2-1
List of Sensor Needs (Continued)

	Item	Cause	Result	Update Interval	Probability	Consequence	Sensing Technologies
14	Connector Splice	Workmanship, thermal cycling, age	Line Down, Fire	1 year	Med	High	Direct Contact Temperature, IR Temperature, Ohmmeter, RFI, E-MAT, MSS
15	Hardware	Age	Line Down, Fire	6 years	Low	High	Optical, IR Spectroscopy
16	Phase Spacer	Age, galloping event	Line Down, Fire	6 years	Low	Med	Optical, UV, RFI
17	Aerial Marker Ball	Vibration Damage, Age	Safety concerns	1 year	Low	Med	Optical, UV, RFI
18	Structure (Steel Lattice)	Corrosion	Reliability concerns	10 years	Med	Med	Optical, IR Spectroscopy
19	Structure (Steel Lattice)	Bent, damaged members	Reliability concerns	1 year	Med	Med	Optical, Strain, Position, Tilt
20	Structure (Steel Pole)	Corrosion, age	Reliability concerns	10 years	Med	Med	Optical, IR Spectroscopy
21	Structure (Steel Pole)	Internal Deterioration	Reliability concerns	1 year	Med	Med	Optical, MSS, Ultrasonics
22	Foundation (Grillage)	Age, corrosion	Reliability concerns	10 years	High	High	Excavation, MSS, Radar, GPR Imaging, Half Cell, Voltage Potential
23	Foundation (Anchor Bolt)	Age, corrosion	Reliability concerns	10 years	Low	High	Optical, Ultrasonics, E-MAT, Vibration
24	Foundation (Preform)	Age, corrosion	Reliability concerns	10 years	Med	High	Optical, Ultrasonics, E-MAT, Vibration
25	Foundation (Stub Angles)	Age, corrosion	Reliability concerns	10 years	Low	High	Optical, Ultrasonics, E-MAT, Vibration
26	Foundation (Direct Embedment)	Age, corrosion	Reliability concerns	10 years	High	High	Excavation, MSS, Half Cell, Voltage Potential
27	Foundation (Anchor Rods, Screw-In)	Age, corrosion	Reliability concerns	10 years	High	High	Excavation, MSS, Half Cell, Voltage Potential, Ultrasonics
28	Grounding	Age, corrosion, tampering	Reliability, Lightning, Safety concerns	6 years	Med	Med	AC impedance, DC resistance, Impulse
29	TLSA (Transmission Line Surge Arrestor)	Lightning Strikes, age	Reliability, Lightning concerns	1 year	Med	Med	Optical, IR, Leakage Current, Lightning Strike Counter

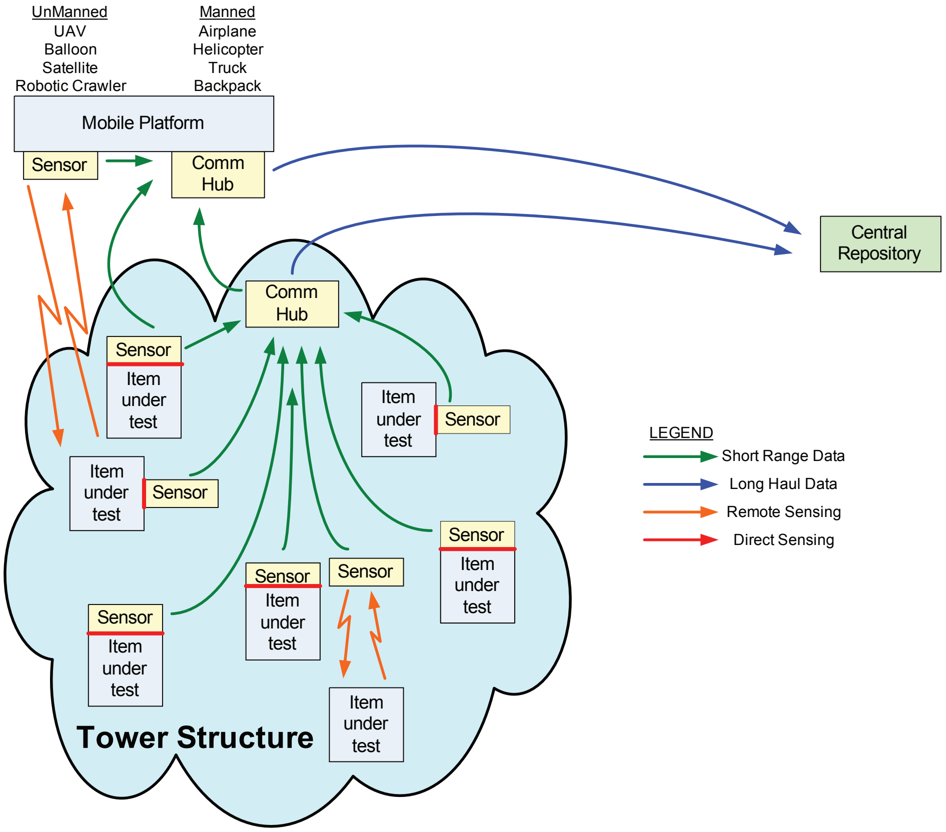

Figure 2-4
Sensor System Architecture and Data Flow

For flexibility, multiple protocols at the physical layer may be used for both short range communications between sensors and hubs, and long haul communication between hubs and the central repository. Consequently, every hub type need not read every sensor type, and every hub type need not communicate with the central repository. There may be applications where relaying readings from one hub to another is an effective method to communicate data back to the central repository. Similarly, relaying readings between sensors before reaching a hub is also an acceptable communications approach.

With regard to the handling of sensor data, there are system tradeoffs between processing power, communications bandwidth, and digital storage capacity. The system must be flexible to allow different sensor applications to handle these tradeoffs differently. For example, in some applications it will be most efficient and optimum to process sensor data locally at the sensor and to report back the reading as a simple answer, e.g. "no encroachment detected". In other applications it may be desirable to have all of the information communicated back to the central repository for archival and possibly even human interpretation. In the former case, the amount of data to be passed through the communication channel is very low (1 bit, maybe once a day), but the processing power required at the sensor may be high in order to make an intelligent decision with high confidence. In the latter case, the amount of data passed through the communications channel is very high (maybe 10M byte for a high resolution image), with much greater potential for impact to system throughput and storage space. The latter approach may be merited when automated results are questionable and manual interpretation of the raw data is required.

Hybrid sensing protocols or approaches may be advantageous and are supported by the system architecture. For example, a flag sensor may simply indicate when an condition needs to be further evaluated; Whether done remotely or while in the field, it may be desirable to interact with the sensor in order to control the amount of detailed data that is provided. The flag sensor may conserve power by not communicating until there is a problem. One possibility is an intelligent sensor that monitors a system condition, and then, based on the sensed severity, applies a commensurate amount of on-board resources (power, processing, memory, communications bandwidth) in order to operate effectively and with high efficiency.

The key functional features of sensors and hubs are illustrated in **Figure 2-5** and **Figure 2-6** respectively. Sensors typically require a source of power, a sensing mechanism, a controller to format measurements into readings, and a short range wireless data communications mechanism. Communications hubs have similar needs for power and controller functions, and in addition need wireless data communication mechanisms to collect sensor readings (short range) and to relay sensor readings to the central repository (long range). Hubs may also have local memory for storing readings, either to buffer data when communications links are down, or as a local repository for data archival/backup.

Although the functional differences between sensors and hubs are delineated in these diagrams, device implementation is flexible to combine features. In other words, hubs can also incorporate sensors and sensors can also serve as hubs, it is not a requirement that they are separate devices. For example, a hub could have a weather station hardwired into it, as well as built-in tower tilt and vibration sensing, for added value. A distinguishing feature of a combinational device that is thought of as a "sensor" versus a "hub" may be its power source. Sensor devices are in general expected to harvest power from the environment and thus require very low maintenance, preferably none. Whereas hubs are in general expected to be more complex, requiring possibly significant power sources such as large batteries, and thus would require periodic maintenance.

Conceptually, sensors use a short range wireless link to the hub which uses a long range wireless link to the central data repository. This is not a requirement, but is based on the vision that many low-cost, low-power, low-bandwidth sensors will be deployed at a tower site, and that a local hub can help by collecting this data, providing a local redundant data repository, and coordinating long haul communications.

2.2 Communications Considerations

A communications system for the instrumented tower concept provides a means for communicating sensor data at transmission line structures to a central data collection and processing facility. A system for large-scale, distributed monitoring and control is termed a Supervisory Control and Data Acquisi-

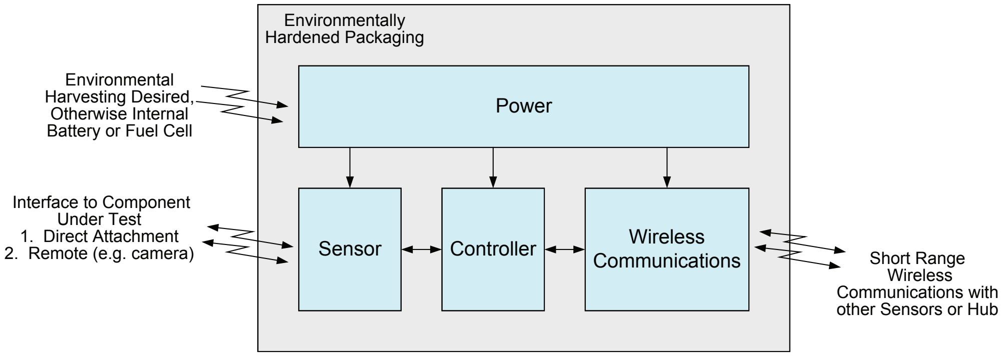

Figure 2-5
Sensor Functional Diagram

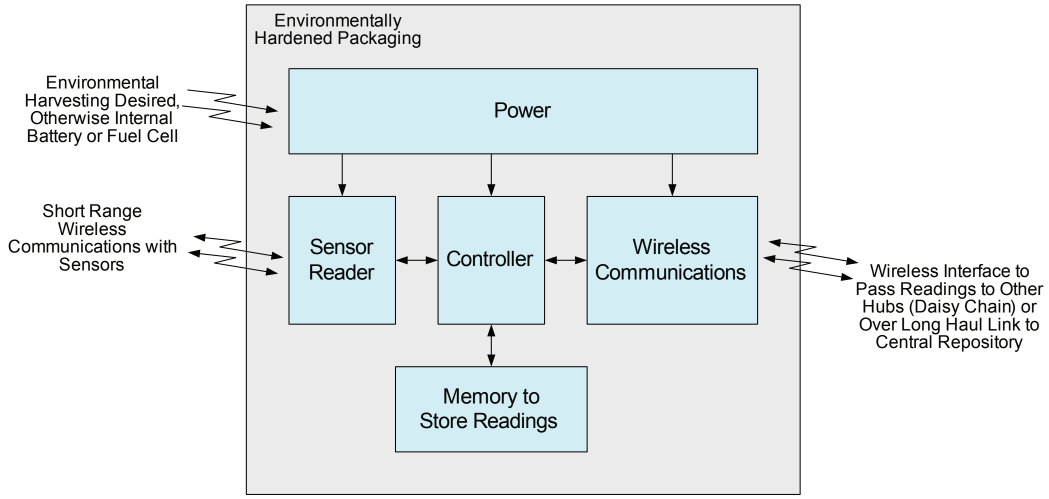

Figure 2-6
Communications Hub Functional Diagram

tion (SCADA) system. SCADA systems for wide-area monitoring have long been in existence and offer reliability enhancements for electrical power transmission systems. The instrumented tower concept requires a customized implementation based on the sensor population, data rates, and ranges, that can be interfaced into the central facility SCADA system or operate standalone running its own SCADA. This project does not address the SCADA layer, it instead focuses on the hardware making sure that the system is realizable with the proper protocols in place.

Both the transmission line infrastructure and the sensors used for monitoring the infrastructure define the requirements for the operational characteristics of the instrumented tower communication system. The primary considerations are distance over which the data needs to be communicated (referred to as range) and the amount of data to be communicated in a period of time (referred to as data rate).

Communication system range is influenced by several factors. The structures under consideration are steel poles and steel lattices installed over hundreds of miles, and the data that is generated locally needs to be collected at a central facility that may be tens to hundreds of miles away. Structures typically range from 80 to 140 feet in height, although there are extreme cases as high as 300 feet. Structures are typically separated by 500 to 1,800 feet, although sometimes they may be closer.

A variety of sensor configurations are envisioned within the system concept. Some sensors will be attached directly to transmission line components, for example conductor splices. Other sensors will be mounted to the structures themselves in order to monitor the structure integrity. Sometimes sensors mounted on structures will be used to monitor the condition of other components and structures, for example a camera with a high F-number lens might monitor a neighboring tower for tampering and right-of-way activity between towers. The need for these different sensor configurations leads to a distributed sensing system. The communications system will need to coordinate the collection of data from many distributed sensors for transfer to a central facility.

The distributed location of sensors imposes several constraints on the sensor design. Sensors on the conductors between towers need to be small, low power, and have a local power source with a limited power producing capacity. Sensors on the tower structure can be larger in size and power consumption. The constraints of the sensor also apply to the technology selected for communicating the sensor data. Because low power consumption is the most restricting constraint for the sensors between towers, the communication technology is consequently relatively short-range and infrequent to keep power consumption at a minimum. The opposing requirements of low power consumption and short range communication versus needing to collect data at a far away central facility influence the architecture of the communication system.

The required data rate is defined by the type of sensor technology. The temperature sensor for a splice transmits a very small amount of data, and the data is required infrequently. Thus, the aggregate data rate is very low. Conversely, the camera output could be a sequence of frames or a continuous video output that would need to be communicated using a high-speed and possibly continuous data link. The data rate influences the power requirements for the communication technology.

Since hubs will likely require much higher power consumption than sensors in order to support long range communications and greater bandwidth, it may be beneficial to incorporate a large solar panel with battery at the hub. This would dictate additional logistics and periodic maintenance, but the tradeoff may be worthwhile. On the other hand, it would not be desirable to do that for a large population of sensors.

Data from each sensor cannot be directly transmitted to the central facility due to range and power consumption trades. Thus, the communication system requires data communication relays. A number of architectural options for the communication system are available to accomplish this:

1. Sensor to passing mobile platform (e.g., robot or a low altitude air vehicle like a UAV or a helicopter) to central facility.
2. Sensor to sensor, daisy chained to central facility (e.g. a mesh network).
3. Sensor to over-the-horizon platform (e.g., balloon or a satellite) to central facility.
4. Sensor to hub on a nearby tower. The hub has the similar options of hub to passing platform, hub to hub, and hub to over-the-horizon platform for passing data to a central facility, except that the hub can possibly be longer range and higher transmitted and consumed power.

Daisy chaining sensors and/or hubs results in an additive effect on the quantity of data to be communicated at each node. However, the very low duty cycle and data rate of many of the sensors make daisy chaining possible for certain sensor technologies. Higher data rate sensors may require more restrictions on the number of devices sharing a communication channel. A combination of daisy chaining and long haul communications may be an effective compromise. For example, towers 1–20 could operate as a daisy chain with tower 20 transmitting back to the central facility. The next 20 towers could be configured the same way.

Range and data rate effect the communication system architecture and a number of architectural options should be considered during the evolution of the instrumented tower concept. To assist the architectural development process, the fundamental performance characteristics of the communications system are outlined in **Table 2-2** along with a rough assessment of the associated requirement for the instrumented tower system concept.

2.3 Power Considerations

Sensors and communications hubs will require power for operation. While batteries may be convenient to test and demonstrate the system, they are seen as a maintenance problem in the instrumented tower concept. The goal is to use renewable power sources in lieu of batteries. This is a difficult challenge, especially for wide range high bandwidth data communications requirements. With present technology, it is not really possible to implement a batteryless system except for very limited and simple scenarios. Even over the next 20 years, without significant breakthroughs this will remain a difficult challenge, albeit a worthy one to keep in mind as new technologies are introduced.

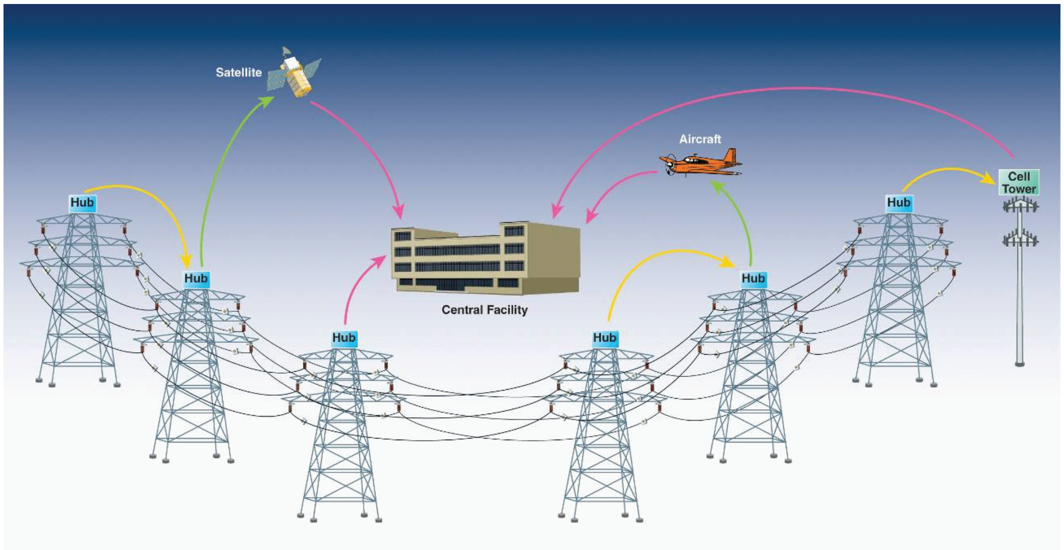

Figure 2-7
Communications Networking Concept

Alternatives to batteries include solar, wind, kinetic (line vibration), thermoelectric, radio waves, and the electric and magnetic fields that are generated from the power lines themselves. There are significant limitations with each of these alternatives, but in the right application they may be effective. For example, the EPRI splice sensor (discussed later under candidate technology), when attached to transmission lines that carry 100 Amps and greater currents, can harvest the magnetic field that is generated by that current, and in turn power the sensor without the need for a battery.

The use of a rechargeable battery coupled with power harvesting may have strong merit. The present challenge with this approach is overcoming a limited number of recharge cycles and low temperature operation, but even a compromise solution may still hold high value now while technology improvements are anticipated.

Potential for Harvesting Power from Line Vibration

For sensors located on or very near a conductor, such as splice sensors or insulator sensors, energy harvesting using vibration may be a possible solution.

Wind causes Aeolian vibrations to occur in transmission lines, the frequency and amplitude of which are determined by the wind velocity normal to the conductor length and the diameter of conductor. For a typical transmission line application using ACSR Drake conductor, vibration displacement amplitudes in the frequency range of 17–35Hz are typically on the order of 5%–12% of the conductor diameter when one vibration damper is used on the line, and between 3%–8% of the conductor diameter when two vibration dampers are used.[1] Using the standard diameter of Drake conductor of 1.108 inches, the anticipated vibration displacement in the frequency range of 17–35Hz is between 30 and 100 mils. This corresponds with acceleration levels of approximately 0.1g–0.7g.

The most common approaches to converting vibration energy into electrical power are through electrodynamic (moving coil through a magnetic field) and piezoelectric (conversion of strain energy to charge in polarized materials) transduction. Piezoelectric energy harvesting has been

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[1] Transmission Line Reference Book, Wind-Induced Conductor Motion, Electric Power Research Institute, 1979.

Table 2-2
Performance Characteristics for Analysis of Communication Technologies

Characteristic	Description	Assessment of Requirement
Range	Distance between communication nodes (i.e., a transmitter and receiver), which can vary between tens of feet for line to tower communication or hundreds of miles for tower to central data collection facility communication.	Short range: several hundred feet (conductor to tower; intra-tower) Medium range: a couple of thousand feet (tower to tower) Long range: up to 100s of miles (tower to central facility)
Frequency Band	Frequency band for transmitting and receiving data, which affects the need for licensing, meeting regulatory standards, maximum data throughput, certain multiple access schemes, and antenna size.	Unlicensed preferred
Network Topology	Architecture for transferring data among system elements. Common network topologies include point-to-point, line, star, ring, mesh, and bus.	Dependent upon communication architecture; most likely a point-to-multipoint topology
Link Availability	Access to the communication channel as determined by line of sight constraints, methods for establishing a link, including link initiation and synchronization protocols; and certain aspects of multiple access methods including time-slot restrictions, spatial diversity, and duplexing method.	Burst modes (low data rate/duty cycle sensors) Continuous (video sensors)
Link Robustness	Ability to establish and maintain the communication link when the channel is degraded by such factors as rain, atmospheric conditions, interference, jamming, dense foliage, urban canyons, and multipath. Robustness is determined by link margin, frequency use, frequency diversity, bit error detection and correction techniques, and communication protocols (e.g., transmit-only or acknowledge with retry protocols).	Required, but minor outages may be acceptable
Data Throughput	Amount of data through the system in a given time period, as limited by the data rate (bits/second) of the transmission, continuous or bursty nature of the transmission, type of modulation, message length, number of message bits that contain user data, two-way communication duplexing techniques, media access restrictions, collision handling and avoidance schemes, and acknowledgement protocols.	kbps (low data rate/duty cycle sensors) Mbps (video sensors)

Table 2-2
Performance Characteristics for Analysis of Communication Technologies (Continued)

Characteristic	Description	Assessment of Requirement
Data Availability	System latency, which is the time the data was sent until the time the end user receives the data, as affected by the system architecture and data distribution systems.	Hours, to days, to months
System Capacity	Number of simultaneous users and total number of users in a system as limited by constraints of the signal processing system and multiple access methods defined by frequency use, collision avoidance protocols, time-slot restrictions, spatial diversity, and duplexing method.	Thousands of sensors
Power Consumption	Amount of power consumed by the communication equipment on the sensor to communicate data, which defines the types and capacities of power source for a particular sensing application. Power consumption is primarily affected by the data rate and communication range of the communication equipment for a given technology.	Very low power (microwatt) Low power
Size	Dimensions of the communication equipment including the electronics, power source, power regulation and control circuitry, and antenna. The size is dependent upon the technology used and is influenced by the transmitted RF power necessary to close the link, complexity of the transmitted waveform, and the necessity of a receiver if two-way communication is possible and/or necessary.	As small as practical
Maturity of Technology	Measure of how long the technology has been available, which can indicate the availability and variety of products, the commercial acceptance of a standard or de-facto standard and thus its possible longevity or the importance of long-term support for legacy products.	Low risk, widespread availability, roadmap for longevity
Cost of Communicating Data	Costs of communication equipment development, production, installation, and accessing the infrastructure.	Moderate non-recurring engineering costs, low production costs, and low maintenance and infrastructure operation costs
Human Interface	The need for a person in the loop in order to configure, operate, and maintain the system	Minimize need for human intervention. A highly automated system is desired

shown to be more efficient than electrodynamic harvesting, and several companies are currently developing off the shelf solutions for piezoelectric vibration energy harvesters. One device that is currently commercially available can produce up to 2mW of harvested power for vibration levels of less than 1g.[2] Other researchers have claimed power density values as high as 40mW/cc per g of acceleration.[3]

A review of several research efforts on power harvesting using piezoelectric materials was performed by Sodano, Inman, and Park.[4] In this review, both methods of transduction and methods of energy storage were evaluated. In most applications, energy generated by vibration energy harvesters must be stored for later use. Two methods of storing this energy are the use of storage capacitors and the use of rechargeable batteries. One of the research efforts demonstrated that fully discharged batteries could be recharged without the use of any external power source. The summarized research concluded that rechargeable batteries provided much more versatility than capacitors due to the capacitor's inability to store large amounts of power and the fast discharge rate of capacitors. With optimal vibration conditions and power storage circuitry, efficiencies as high as 50% were experimentally obtained by one research team, and as high as 70% were obtained by another. This is many times higher than the most efficient solar cells currently available.

As technology evolves, vibration harvesting may provide a viable and affordable means of powering distributed sensors, though their application for the smart transmission line concept will probably be most feasible on those sensors located on or near a conductor.

Potential for Harvesting Power from the Wind

A windmill developed by S. Priya [reference Priya S., Applied Physics Letter 87, 184101 (2005)] of approximately 10 cm across, is attached to a rotating cam that flexes a series of piezoelectric crystals as it rotates. Piezoelectric materials generate a current when they are squeezed or stretched, and are commonly used to make a spark in gas lighters. Priya has found that a gentle breeze of 16 km per hour can generate a constant power of 7.5 milliwatts, which is adequate to operate many types of electronic sensors. A conventional generator that used a 10-cm turbine would convert only 1% of the available wind energy directly into electricity, but a piezoelectric generator can convert up to 18%, which is comparable to the average efficiency of the best large-scale windmills, according to Priya. Priya has also patented a much smaller device, measuring just 0.5 cm a side, which is driven by a smaller turbine fitted with tiny wind-catching cups, similar to the devices used by meteorologists to measure wind speed.

Potential for Optical Power Transmission

Non-conducting fiber optics can be used to transmit small amounts of power, although the efficiency is low. The system consists of an optical source (LED or laser diode) coupled to a fiber optic cable that delivers the light to a photovoltaic junction.

Assuming a 1 watt laser diode or super-bright LED source, rough calculations indicate that 10 to 30 mW of power can be generated at a photovoltaic junction (solar cell). This is based on 50% efficiency coupling to and from the fiber optic and 4 to 8% photovoltaic conversion efficiency. This example of energy conversion efficiencies is only a guide; more accurate calculations with specific components and laboratory confirmation should be done if this is to be considered as a viable power option.

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[2] http://www.mide.com/prod_energy_harvester.html#specifications.

[3] http://www.omegasensors.com/datasheets/Energy%20Harvester%20Flyer.pdf.

[4] "A Review of Power Harvesting from Vibration Using Piezoelectric Materials", The Shock and Vibration Digest, 2004.

Although this efficiency of 1 to 3% is very low, there are cases where this method may be useful for powering a remote sensor. For example, if a solar panel and battery is located on top of a tower, a sensor at the base of the tower could be operated by a two-fiber cable down the tower. One fiber would carry power and the other would be used to transmit control and data signals. For micropower sensors that are operated only a few minutes a day, the low efficiency may not be a factor.

Potential for Other Power Harvesting Methods

There is good potential for other power harvesting methods as well, although a technical review of these technologies is not a focus of this report. In close proximity to a transmission line system, the high electric and magnetic fields can be harvested as is demonstrated by the EPRI splice sensor. Solar power is also recognized as a prime candidate.

3

CANDIDATE TECHNOLOGY FOR THE INSTRUMENTED TOWER

There are many sensor, data communications, and mobile collection platform technologies that could be applied to the instrumented tower concept. This report attempts to address and provide insight into some of the enabling technologies that appear to be suited for the application. Candidate technologies are examined with regard to their suitability and state of readiness for the application, expectations for development potential over the next 20 years, and design constraints such as power requirements, physical requirements (size, weight, attachment, durability), and data/bandwidth requirements where applicable.

This section of the report is organized into three main areas as follows:

1. Sensing technology
2. Data communications technology
3. Mobile collection platforms

3.1 Sensing Technology

Sensing needs were a focus of the kickoff meeting and are documented in **Table 3-1**. Insight into some of the sensing technologies that were identified as candidates to meet those needs is provided in this section, organized as follows:

1. Optical Image Sensing
2. Infrared Image Sensing
3. Ultraviolet Image Sensing
4. Satellite Image Sensing
5. LIDAR
6. Vibration Sensing
7. Acoustic Sensing
8. Strain Sensing
9. Tilt Sensing
10. Magnetostrictive Sensing (MsS)
11. Ultrasonic Sensing
12. Electromagnetic Acoustic Transducer (EMAT)
13. Eddy Current Sensing
14. Ground Penetrating Radar (GPR)
15. Proximity Sensing
16. Voltage Potential and Half Cell Measurement
17. Radio Frequency Interference Sensing
18. Leakage Current Sensing
19. Direct Contact Temperature Sensing
20. Lightning Sensing and Counting

Table 3-3 below summarizes the technologies above addressed in this report and maps them to categories of sensing applications derived from the needs documented in Table 2-1.

Table 3-1
Summary Table

	Candidate Technologies (2.1)																				
	Optical	Infra-red	Ultra-violet	Satel-lite	LIDAR	Vibra-tion	Acoustic	Strain	Tilt	MsS	Ultra-sonic	EMAT	Eddy Current	GPR	Prox-imity	Voltage Poten-tial Half Cell	RFI	Leak-age Current	Temper-ature	Light-ning	
Application	3.1.1	3.1.2	3.1.3	3.1.4	3.1.5	3.1.6	3.1.7	3.1.8	3.1.9	3.1.10	3.1.11	3.1.12	3.1.13	3.1.14	3.1.15	3.1.16	3.1.17	3.1.18	3.1.19	3.1.20	
																					COUNT
Mechanical/Structural Integrity																					
Foundation						x				x	x			x		x					5
Tower Structure	x					x		x	x	x	x	x	x			x				x	10
Hardware	x																				1
Connectors, Splices	x											x									2
Conductors	x											x									2
Electrical/Operational Integrity																					
Connectors, Splices		x																	x		2
Conductors		x																	x		2
Insulators		x	x			x											x	x			5
Transmission Line Surge Arrestors		x	x														x	x		x	5
Clearance																					
Trees	x			x	x										x						4
Avian	x				x	x	x								x						5
Encroachment	x			x	x	x									x						5
Line Sag	x				x										x						3
Galloping conductors	x														x						2
Security																					
Tampering (in process)	x					x	x								x						4
Tampering (result of)	x			x					x												3
COUNT	11	4	2	3	4	6	2	1	2	2	2	3	1	1	6	2	2	2	2	2	

3.1.1 Optical Image Sensing

Optical imaging includes methods in which an image provided by a camera is interpreted by computer analysis to identify or detect specific conditions. Different camera systems can provide image representations in visible, infrared or ultraviolet spectral bands and each of these bands has advantages for detecting different conditions or defects. There are also a variety of methods for positioning or deploying imaging cameras with some choices more suitable for detecting certain types of defects. Optical imaging is the automated analog of current visual inspection methods and has potential application for a high percentage of the transmission line components to be inspected.

Image Analysis

Computer analysis of images to detect specific conditions or abnormalities is widely used in manufacturing and other well-structured areas where images are obtained with consistent lighting, viewpoint, magnification and other factors. Analysis of outdoor images with wide variations in illumination is more complex but adaptive methods are available to compensate for changing conditions of sun and shadow. Statistical methods are used to normalize image intensity and minimize the effects of slowly changing artifacts such as shadows and glare spots.

Computer analysis typically consists of several steps:

1. Image capture using monochrome, color, infrared or ultraviolet cameras. The image is converted to a digital representation either internally in a digital camera or by a frame grabber if an analog camera is used.
2. A filtering step is usually included to remove image noise, normalize illumination or enhance image contrast.
3. The image is segmented to identify regions that correspond to physical object such as trees, towers, insulators or conductors. Segmentation algorithms may be based on finding edges, corners or other shapes. Segmentation may also be based on color differences or difference in image texture or other patterns.
4. Each object identified in the segmented image is characterized by describing a set of features. These feature sets include measurements of intensity, area, perimeter, shape, color and connections to other objects.
5. Feature sets are matched against a database to identify specific types of objects. For example a large green object with a generally round shape would be classified as a tree or bush while a long thin object with no connection to other objects could be classified as a conductor between towers.
6. Finally, analysis of each object is done by comparing specific characteristics of the observed object with conditions specified in the database. In the case of a tree or bush, the comparison might be related to the position in the right-of-way while in the case of a conductor; the condition might be the amount of mid-span sag or the absence of a marker ball.
7. If certain conditions are met or not met, the computer system would signal to an operator for corrective action.

The condition of transmission lines changes really slowly and there is a relatively low level of activity on and around a line. This may make the processing of images more feasible. However many of the conditions that are being inspected for are hidden from clear view or require multiple lines of sight making it difficult. With this in mind, three primary approaches to camera deployment and image processing are discussed below.

Fixed Cameras- Image analysis is simplified when cameras are mounted at fixed locations with fixed orientations. This facilitates storing a reference image for comparison with the current image to determine if anything has changed. For example, a camera mounted on a tower could capture images showing the right-of-way under the conductors and compare with a reference image. If image analysis detects any new object in the current image, this would be interpreted as encroachment in the right-of-way. A similar approach could be taken to evaluate component degradation.

Pan/Tilt Mounts with Zoom Lenses- The fixed camera approach simplifies image analysis but would require more cameras than a method that utilizes cameras with azimuth and elevation (pan and tilt) control and possibly a zoom lens. Such a camera, mounted on a tower, could be controlled to execute a repeated observation of a transmission line span using a raster scan with the zoom lens increasing image magnification for more distant views. As illustrated in the figure below, a mosaic of 50 to 100 images will provide good detail of the right-of-way between towers, conductors in the span and the hardware of adjacent towers. Image analysis software would have to include inputs of the elevation and azimuth positions to determine the location of the image frame. This would be used to access a data base listing the types of objects expected in each frame for comparison with the objects found in the current image. A complete visual tour of spans forward and backward from the camera could be done in 10 to 20 minutes so inspection strategies could range from continual scans to detect possible vandalism or terrorist acts to once-a day or even less frequent scans to provide time for solar cell battery charging.

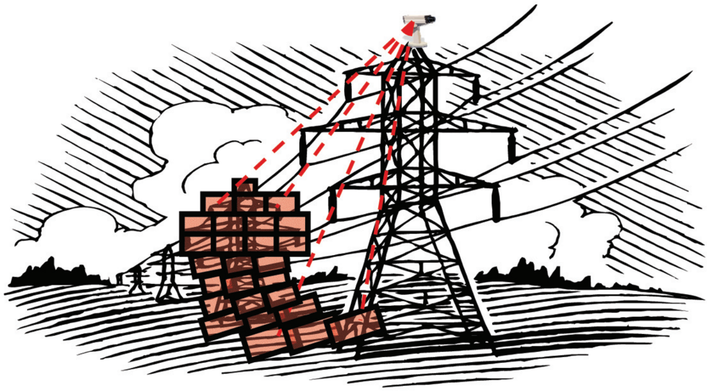


Figure 3-1
Mosiac of Images from Pan/Tilt Camera Mounted

Movable Cameras- Additional flexibility can be introduced by mounting the camera, with pan/tilt/zoom positioning, on a platform that can move along the transmission line span. The figure below illustrates the concept of a camera mounted on a robot that can move along a static wire to traverse multiple spans of a transmission line. In this case image analysis and comparison would include GPS coordinates of the robot location as well as of the elevation and azimuth orientations to determine the location of the image frame. The inspection strategy would most likely involve moving the robot to specified GPS coordinates and then capturing a sequence of images at predetermined elevation, azimuth and zoom settings. Objects identified in each frame would be compared to objects in a database for all frames of view along the transmission line. The imaging system could perform a complete video tour and analysis from one location in 10 to 20 minutes and the robot would then move to the next inspection location, possibly 400 to 600 yards along the span. If power requirements can be met, this should result in inspection of 2 to 5 miles of line per day.

Another approach would be to install a camera on a Unmanned Aerial Vehicle (UAV). This would have the advantage of a faster inspection time and ability to be deployed in storm response situations.

Figure 3-2
Camera Mounted on Static Wire Robot

Cameras

Mass production of components for consumer digital cameras has resulted in improved performance and reduced cost for cameras intended for automated computer image analysis. A large number of monochrome and color cameras with resolutions ranging from 640 x 480 pixels to 2K x 2K pixels are available and image resolutions are expected to increase in the coming years. Signal interfaces range from the conventional RS-170 analog signals to standard digital interfaces including USB, IEEE 1394 (Firewire), CameraLink and GigabitEthernet as well as wireless modes. In the future we cans expect to see fewer analog cameras and more high-speed digital transmission, especially wireless. Many cameras include electronic shutter control allowing extended exposure times for low light operation. Black and white cameras are more sensitive than color cameras. Sensitivity and SNR are primarily functions of the CCD imaging arrays and significant improvements are not expected in the near future.

Summary of Cameras and Image Processing	
Commercial technology options	Color and monochrome cameras are being applied in many outdoor surveillance applications. Very little software specifically developed for automated transmission line inspection is available but the building blocks for developing such applications exist.
Expected improvements over the next 20 years	Cameras and image processing computers will become physically smaller with higher resolution and greater processing capability in the future. As computer power increases, image analysis algorithms will become more capable, approaching artificial intelligence goals.
Physical interface requirements	Optical methods are non-contact. Cameras can be equipped with telephoto lenses to increase the stand-off distance though this reduces the field-of-view. Zoom lenses can be used to provide large scene overviews and highly magnified views of critical locations.
Power requirements	Typical voltages are 5 VDC and 12–24 VDC. Power consumption is typically 1 to 5 watts.
Data/bandwidth	Video data rates are required between the camera and image processing computer but data from the camera-computer system will be low bandwidth, digital data describing a specific condition identified by image processing. In addition, it would be desirable to transmit images of the condition for reference or additional interpretation by an operator. Digital images would be in compressed format and might range from 50 to 300 kilobytes.
Size/weight	From 1″ x 1″ x 1″ to 2″ x 2″ x 4″ and weighing from a few ounces to a pound.

Smart Cameras- Several manufacturers supply cameras with image processing computers built into the case. All standard image analysis routines can be programmed in these "smart cameras", eliminating the need for a separate image analysis computer. In addition to standard video output, these camera systems include USB and wireless interfaces so the results of image analysis can be reported over a low bandwidth channel. They also provide the capability of transmitting compressed images at low data rates when it is desirable for an operator to see a scene to verify a conclusion or decide of a course of action. Some of these smart camera computers can accept other input signals so they could potentially provide all of the computational functions of a sensor node.

Summary of Smart Cameras	
Commercial technology options	Sony, VC Vision and others provide monochrome cameras in rugged housings. The Sony system is based on a 400 MHz x86 architecture and is compatible with a number of image processing software packages. The VC Vision system is available with either color or monochrome imager and uses a 400 MHz processor from TI.
Expected improvements over the next 20 years	The variety and capability of smart cameras will increase rapidly. The systems will become physically smaller with higher resolution and greater processing capability. As computer power increases, more complex image analysis algorithms and software will be included with these systems.
Physical interface requirements	Optical methods are non-contact. Cameras can be equipped with telephoto lenses to increase the stand-off distance though this reduces the field-of-view. Zoom lenses can be used to provide large scene overviews and highly magnified views of critical locations.
Power requirements	Values for the Sony system are: 10.5 to 26.4 volts with 7.5 watts.
Data/bandwidth	The camera-computer provides Ethernet, USB 1.1 and RS-232 interfaces as well as digital i/o lines that could be used to control/sample other sensors. Data transmitted from the system will be low bandwidth, digital data describing a specific condition identified by image processing. Digital images would be transmitted in compressed format and might range from 50 to 300 kilobytes.
Size/weight	The Sony camera can be considered typical for this group. It is 2.3" x 2.2" x 4.5" and weighs 14 ounces.

Applications of Optical Imaging

Computer analysis of camera images can be used for automated detection of a wide range of defects that are currently found by visual observation. Encroachment on the ground or on towers can be identified by detecting objects in locations that should be clear. Wires and conductors can be inspected and broken strands that extend away from the surface of the cable can be detected. Images of insulators can be analyzed and the presence of contamination or physical damage (such as gunshot damage) can be detected. The condition or absence of phase spacers or marker balls can be determined by image analysis. Also, tower tampering by terrorists or vandals could be promptly identified in order to alert authorities.

The condition of structural components can be evaluated by image analysis although this is more complex. Edge and line detection algorithms would be used to identify lattice objects and these would be compared to database entries to determine if any are missing, bent or out of position. The surface patterns of steel poles or lattice members would also be analyzed to detect patterns that would indicate rust, corrosion or other surface damage.

The effectiveness of inspecting components such as insulators and tower members will depend on the camera position and the viewing angle. If a single camera is mounted at the top of each tower, it will not be in a good position to see the insulators and lattice members of that tower and it will be a long distance from the adjacent towers. A camera on a line crawling robot would have the advantage of seeing the tower and insulators from several different positions and the robot moves toward the tower.

3.1.2 Infrared Image Sensing

Infrared cameras are sensitive to longer wavelengths than conventional color cameras. The most useful infrared band for transmission line inspection is long-wave or thermal IR, from 8 to 14 micron wavelength. Early thermal infrared cameras used a single detector with a scanner to build up an image but current systems use microbolometer arrays and quantum well devices fabricated with typical resolution of 320 x 240 pixels. Many infrared camera systems today are designed for operators conducting thermal surveys and include image enhancement software and an LCD viewing screen. Most are intended for use at fairly short range and long focal length lenses (made from germanium) are expensive. Radiometric cameras are calibrated so that an accurate surface temperature can be read from the thermal image. Non-radiometric cameras provide an indication of relative temperature but do not give an absolute temperature.

The amount of infrared radiation from a source depends on the temperature of the surface and also on the emissivity of the source. Very smooth or shiny surfaces emit a smaller amount of radiation than rough or dull surfaces. Accurate temperature measurements require knowledge or assumptions of the surface emissivity. When the surface condition is unknown it is still possible to identify hot spots by determining temperature differences even though the absolute temperature cannot be measured.

IR cameras are often classified as cooled or uncooled. High-end thermal IR cameras often provide a peltier or compressor system to cool the detector to reduce the effect of thermal noise. Uncooled cameras typically are less expensive, smaller and use less power but will be less sensitive and have more image noise . Costs for thermal infrared cameras range from $7K to $50K depending on the features, resolution, accuracy and lenses included.

Some IR cameras, such as the OEM Photon from Indigo or the Cantronic Thermal Ranger, are intended for integration into automated surveillance or inspection systems. Compared to handheld systems intended for operator use, these cameras are small, compact and have low power requirements. These would be suitable for an automated transmission line inspection station when used with custom image analysis software.

In the transmission line inspection systems, thermal IR cameras are most often used to identify hot spots caused by leakage current dry band arcing on insulators or failing connections, e.g. splices o dead ends compression connectors. One alternative to a complete IR camera system is to include an infrared thermometer, which is a single IR detector with optics to focus radiation from a small area on the detector (essentially a 1x1 pixel camera). The IR thermometer would be mounted and bore-sighted to a conventional camera on a pan/tilt mount. Image analysis would be used to aim the thermometer at locations in the image where elevated temperatures might indicate failing components. Slight variations in the orientation could be used to build up a thermal image of a component. This process would be very slow compared to an array IR camera but might be a useful low cost alternative for a camera station placed on a tower where actual imaging will be required only a small fraction of the available time.

Applications of Infrared Imaging

Infrared imaging can be used to detect heat generated by insulator leakage currents or failing components such as a conductor splice. With appropriate image analysis, it could be used for automated detection of failing insulators or damaged conductors.

Summary of Infrared Imaging	
Commercial technology options	Systems suitable for outdoor use and transmission line inspection by an operator are available from several manufacturers. Most are battery powered and include image processing functions to enhance and measure temperature differences. IR imagers (without specialized image processing functions) are also available. Additional image analysis would be required for automated identification of thermal hot spots indicating a problem.
Expected improvements over the next 20 years	The image resolution of IR cameras will increase as nanotechnology techniques are applied to microbolometer arrays. IR cameras will be produced in greater variety and greater volume due to use in the surveillance and security areas. The increased volume will result in lower unit prices. "Smart IR cameras", including a programmable image processing computer will be available. Digital interfaces, including USB, Firewire Ethernet and wireless will be included.
Physical interface requirements	As an optical method, thermal IR imaging is non-contact. Stand-off distances can range from several feet to several hundred feet if telephoto lenses are used.
Power requirements	Typically 7–15 VDC 2–15 watts for uncooled cameras
Data/bandwidth	The camera video interface is typically NTSC or PAL. After image analysis, data transmitted from the system will be low bandwidth, digital data describing specific conditions identified by image processing. Digital images would be transmitted in compressed format and might range from 50 to 300 kilobytes.
Size/weight	Dimensions from 2" x 2" x 4" (excluding lens) to 4" x 5" x 9" Weight from .5 lbs to 4 lbs depending on features and lens.

3.1.3 Ultraviolet Image Sensing

CCD imaging arrays can be optimized for detection of ultraviolet light by making the silicon substrate very thin and directing the incident radiation onto the back surface. This overcomes the performance limits of the conventional front-illuminated CCDs by illuminating and collecting charge through the back surface away from the polysilicon electrodes. Ultraviolet cameras, sensitive to wavelengths shorter than the visible spectrum are widely used in astronomy and for inspection of silicon wafers. Many manufacturers of CCD arrays and video cameras offer "UV enhanced" versions for QA or process inspection.

The primary use of UV cameras in transmission line inspection is to locate corona sources. One of the difficulties of detecting corona on transmission lines is that the large UV content of solar radiation is much greater than typical transmission line corona sources. In order to detect corona discharge outdoors in the daytime, it is necessary to filter the light to use only a narrow band of the UV spectrum (250–280 nanometers) where solar UV is absorbed by the atmosphere. Cameras using this technique are termed "solar-blind".

Several manufacturers, including Ofil and CoroCam, supply UV cameras for use in transmission line inspection. These are typically intended to be hand-held or mounted on a tripod. The operator will direct the camera at a potential source of corona and observe an LCD screen to determine if a UV source is present. The cameras include controls for adjusting the sensitivity and software for measuring the intensity of corona discharge by counting photon events.

DayCor cameras, manufactured by Ofil, obtain images at both ultraviolet and visible wavelengths that can be combined in the display. This is also a feature of the CoroCam Model 504. This provides the operator with the ability to accurately locate the UV source in relation to scene features. While this is very useful to operator inspections, it may have less value to automated systems that would probably include a separate visible camera from the UV imager.

Applications of Ultraviolet Imaging

Ultraviolet imaging, coupled with appropriate image analysis algorithms, could be used to detect sources of corona and arcing that indicate insulator hardware failure and can cause damage to other components. UV imaging can also detect contamination on insulators and other components.

Summary of Ultraviolet Imaging	
Commercial technology options	The DayCor and CoroCam 504 cameras are specifically designed and manufactured for transmission line inspection by operators. They could be adapted for use in an automated system. Image resolution ranges from 320 x 240 pixels to roughly 450 TV lines (NTSC format).
Expected improvements over the next 20 years	Advances in solid state imagers, electronics, and optics will provide smaller and lighter instruments with higher image resolution. It is very likely that stand-alone cameras will be available for integration into automated inspection systems.
Physical interface requirements	Ultraviolet imaging methods are non-contact. UV lenses are limited in availability and most of these cameras use proprietary mounts and lenses.
Power requirements	12 VDC, 10 to 20 watts
Data/bandwidth	Video signals are available through a PAL or NTSC connector. The systems are generally intended for operator use and would require some modification to make use of the image enhancement and photon counting capabilities.
Size/weight	Roughly 6″ x 6″ x 10″ to 15″ long, 6–15 pounds

3.1.4 Satellite Image Sensing

Since the LANSDAT 1 satellite was launched in 1972, images from space have provided a means of analyzing large features on earth. Several other companies, including GlobeXplorer and Spatial Mapping currently market imagery from LANDSAT satellites or aerial photography services for municipal planning, forestry and agricultural land use analysis and similar applications. The latest LANDSAT (number 7) is in sun-synchronous polar orbit that passes over any given location on earth roughly every 15 days but its resolution of 15 meters/pixel is significantly less than the commercial satellite IKONOS. In 2001, NASA launched EO-1 with a resolution of 10 meters/pixel. Images from the NASA satellites are available and are marketed by companies that process the images to register strips, equalize lighting and correct for optical distortions.

There are also several commercial imaging satellites. GeoEye operates the IKONOS satellite, launched in 1999. It is also in sun-synchronous orbit at an altitude of 423 miles and can provide monochrome images with a resolution of 1 meter/pixel. This orbit passes over given geographical locations every three days.

SPOT Image Corporation operates the SPOT-5 satellite placed in orbit in 2002. SPOT-5 has a revisit time of 2–3 days and provides a maximum resolution of 2.5 meters/pixel. Satellite Imaging Corporation is an official distributor for SPOT Image Corporation.

The next step in commercial satellite imaging is represented by GeoEye-1, scheduled for launch in the 3rd quarter of 2007. GeoEye-1 will be capable of acquiring image data at 0.41 meter/pixel for monochrome images and 1.65 meter/pixel for multispectral images. GeoEye-1 will have a revisit time of less than three days, as well as a three meters positional accuracy.

Higher resolution images (1 foot to 6 inches/pixel) are available from some services such as GlobeXplorer but these are obtained from aerial photography and are available only for limited locations at infrequent intervals.

Applications of Satellite Imaging

The relatively low resolution of current satellite imaging systems makes it impossible to detect many conditions. Even with a resolution of .41 meters/pixel (16 inches/pixel) of the new GeoEye-1, it will not be possible to detect conditions such as damaged hardware or missing marker balls. It should be possible to detect large bushes or small trees in the right-of-way or large avian nests on towers.

Summary of Satellite Imaging	
Commercial technology options	Several companies operate commercial imaging satellites today. Images of selected areas can be purchased for analysis. The current resolution is not sufficient for detecting small conditions but might be used for large objects intruding in the right-of-way or erosion events.
Expected improvements over the next 20 years	More satellites will be launched, especially as other countries obtain the capability or placing systems in orbit. This should result in lower costs and more timely availability of data. It is less likely that there will be significant improvements in resolution since the most recent system (GeoEye-1) is approaching the limits of atmospheric dispersion.
Physical interface requirements	Satellite imaging is a non-contact, long stand-off inspection method.
Power requirements	NA – provided by satellite
Data/bandwidth	NA
Size/weight	NA

3.1.5 LIDAR

LIght Detection And Ranging uses the same principle as RADAR. The LIDAR instrument transmits light out to a target where a portion of the light is reflected back to the instrument. The time for the light to travel out to the target and back to the LIDAR instrument is used to determine the range to the target. The simplest LIDAR instruments are single point distance rangefinders. These have recently found their way into a variety of consumer uses such as measuring distance to golf holes, the size of rooms, area of parking lots, etc. This consumer market has lowered the cost of basic laser rangefinders. Typical laser rangefinders have a range of up to 3000 feet and a range accuracy of +/– 3 ft. These are typically hand held devices without data interfaces and would require modifications for use in an automated measurement system.

More complex LIDAR systems use an optical scanner to direct the laser beam in a fan or raster pattern and measure the distance over a line or area. Line scanning systems are often used on airplanes or helicopters to measure the profile of a strip under the flight path. These systems are often combined with GPS/Inertial navigation technology to ensure stability and uniform measurements. During flight a scanning laser range finder measures the distance to the ground thousands of times per second as it scans a swath below the aircraft. These are typically large, complex and expensive systems. For example, the Leica GeoSystems ALS-40 LIDAR is intended for operation up to 20,000 feet above the terrain and uses a 40 kHz pulse repetition rate. The laser source has a peak power of 11.7 kW @ 15 KHz and a pulse width of 11.8 nanoseconds. The scanning assembly is composed of a Beryllium mirror, galvanometer and encoder providing a variable field of view, up to a maximum of 75 degrees to match the ground footprint of a conventional camera system.

Applications of LIDAR

LIDAR systems could be used to detect encroachment by measuring the height of objects on the ground. If the system is deployed on a line-crawling robot, a line scanning LIDAR, similar to airborne systems could be used to construct the elevation profile of a swath under the line. Any points that rise above the ground level more than a specified amount would be detected as encroachment.

Utilities currently use LIDAR to map their right of ways and determine conductor position. They do this on a very infrequent basis and use the results to design new lines or determine whether their lines meet the NESC conductor to ground clearance requirements.

Summary of LIDAR Systems (Airborne)	
Commercial technology options	Current scanning LIDAR systems are complex and expensive. They are used in research programs and by a few service companies providing GIS and topographic data for land use, municipal planning and mineral exploration.
Expected improvements over the next 20 years	A smaller and simpler LIDAR system with reduced range could be designed if there were a market need. At present there does not appear to be a market that would justify development.
Physical interface requirements	Non-contact
Power requirements	Not known – probably 24 to 120 volts and several hundred watts due to laser power and electronics
Data/bandwidth	Typical image data with a range value at each pixel
Size/weight	Not known

3.1.6 Vibration Sensing

There are many different types of vibration sensors that measure various quantities related to vibration, including displacement, velocity, and acceleration. The most commonly used vibration transducer is the accelerometer. Most commercially available accelerometers are piezoelectric transducers. These use a pre-polarized piece of piezoelectric material that produces a charge proportional to forces acting on it. A piezoelectric accelerometer typically employs a mass (either in a shear or a compression configuration) that produces a force on the piezoelectric element that is proportional to the acceleration experienced by the mass. Many piezoelectric accelerometers contain integral electronics that convert the charge produced by the piezoelectric material to a voltage or current to reduce the sensitivity of cable effects on the measured output.

With the advent of MEMS (MicroElectroMechanical Systems) devices, a new class of accelerometers is now commercially available. MEMS accelerometers are typically capacitive devices that employ parallel plates or interdigitated fingers whose capacitance changes as a function of applied acceleration. MEMS accelerometers are increasingly being used in many commercial applications, such as airbag deployment sensors. Such devices can be produced with extremely small form factors, requiring very little power. Unlike piezoelectric accelerometers, capacitive MEMS accelerometers can respond to DC accelerations, making them appropriate for use as tilt sensors as well as vibration sensors.

Commercially available accelerometers can be obtained in a variety of form factors and with widely varying sensitivities and frequency responses. Piezoelectric accelerometers can be used for sensing vibration with frequencies as low as 0.1 Hz or less, and up to 10 kHz or more. Capacitive accelerometers are available that respond in a frequency range from DC up to a few kilohertz. Transducers are available that are capable of measuring vibration levels ranging from a few micro-Gs to several thousand Gs.

Applications of Vibration Sensors

Vibration data can be used to identify a wide variety of phenomenon, from transient effects to non-destructive damage identification. For high voltage transmission applications, vibration transducers could be used to identify the following items:

- Tampering of towers
- Heavy construction equipment near towers (possible sign of encroachment)
- Avian nesting activity
- Lightning strikes
- Tilt indicating tower damage
- Detect damage in polymer or ceramic insulators (requires separate excitation)
- Detect some forms of foundation damage (requires separate excitation)

For identifying tower tampering, an accelerometer would need to be rigidly mounted to the structure of the tower, preferably near the base of the tower. In this configuration, metallic contact to the tower structure, such as a wrench being applied to the bolts of the tower, would create a high frequency signature that could be identified. As the transducer mounting location is moved further from the base, the probability of identifying the signature would decrease, as the high frequency energy is dissipated in the material and in the bolted and welded interfaces between the base and the transducer. The same location could be used for identifying encroachment of construction equipment, though the frequency range of interest would be much lower in this case. Real-time monitoring would be required for both of these applications.

Avian nesting, lightning strikes, and tilt sensing require the vibration transducer to be located near the top of the tower. Lightning strikes could be identified based on the impulsive vibration occurring in the tower at the moment of a strike. Avian nesting activities would likely be identified based on an increased rms acceleration level in a specific frequency regime. Both of these application would require real-time monitoring of vibration signals. Tilt sensing using accelerometers would require multiple accelerometers capable of dc response. A single tri-axial MEMS accelerometer could be used to measure the acceleration due to gravity simultaneously in each of three orthogonal directions to determine the tilt of the sensor with respect to the ground. Such a sensor could be periodically recorded to detect changes in the tower's tilt due to storms or other occurrences causing structural deformation in the tower.

Research is currently being funded by EPRI to develop a tool to identify mechanical damage in polymer and porcelain insulators using vibration response. The technique uses a mechanical impactor to impart vibration to the insulator. The induced vibration is measured with an accelerometer, and the data is analyzed in the frequency domain to determine if shifts in resonant frequencies have occurred that may indicate the presence of mechanical damage. For this technology to be applied to the instrumented tower concept, both the impactor mechanism and the measurement accelerometer would need to be mounted directly to the insulators being evaluated. This is not currently being considered as an option for the proposed system, but the information is included as a reference for another possible future application.

It is possible that some forms of foundation damage may also be identifiable using vibration analysis. As with the insulator damage detection application, this would require an impactor or some other mechanical device to induce vibrations in the foundation in order to measure its vibration response.

The response accelerometer would need to be directly mounted to the foundation for such a measurement. Algorithms have not yet been developed to correlate specific aspects of foundation vibration response to possible forms of damage that may occur.

Summary of Vibration Sensors	
Commercial technology options	Many types of transducers are commercially available with a wide variety of form factors and performance specifications.
Expected improvements over next 20 years	Vibration transducers will become smaller and require much less power. The most efficient MEMS accelerometers are already available that require less than a micro-watt of power .
Physical interface requirements	Must be directly coupled to item being measured.
Power requirements	Typically range from 1–500 mW
Data/bandwidth	20–50 kS/sec
Size/weight	Very small and lightweight. Typical dimensions: ½″ cube or less Typical weight: a few grams

3.1.7 Acoustic Sensing

Acoustic sensors (microphones) are inexpensive instruments that can be used to measure acoustic pressure fluctuations in a wide range of frequencies and amplitudes. There are multiple types of microphones, including condenser, dynamic, carbon, piezoelectric, and MEMS microphones. Microphones are widely available in many different form factors with varying directional characteristics for specific applications. Many require low amounts of power and are very rugged.

Applications of Acoustic Sensors

For the purpose of monitoring activities on and around high voltage transmission lines, acoustic sensors can be used to identify system tampering, gunshots, and/or avian activity. The advantage of using a microphone rather than an accelerometer for these applications is that the microphone's location and mounting configuration is less critical for proper measurement. However, because microphones sense many other acoustic phenomenon of no concern in this application, significant signal processing may be required to differentiate vandalism or terrorism related signals from other acoustical signals. In the case of a gunshot, the wide frequency content and impulsive nature of the acoustic signature make the signal detection algorithms tractable. However, other forms of system tampering, such as tower vandalism or removal of supporting bolts, may be difficult to differentiate from other acoustical signals of no importance. In this case, multiple acoustic sensors could be used to triangulate the source of the sound to a particular location of concern. However, these signals could be more easily identified from a vibration transducer mounted to the tower structure, with much greater rejection of signals with less importance.

Summary of Acoustic Sensors	
Commercial technology options	Many types of transducers are commercially available with a wide variety of form factors and performance specifications.
Expected improvements over next 20 years	Higher sensitivity, smaller form factor, lower power requirements. New designs using MEMS or nano-technology may surface.
Physical interface requirements	No specific mounting requirements.
Power requirements	Typically range from 1–500 mW
Data/bandwidth	50–100 kS/sec
Size/weight	Small and lightweight. Electret and piezoelectric microphones can be a fraction of an inch across, weighing a few grams or less.

3.1.8 Strain Sensing

Strain measurements are typically made on structural components to determine whether the yield strength of the material has been exceeded or if periodic vibrations are severe enough to cause fatigue problems in the material. Strain is a unitless quantity defined as the change in length of a material due to a stress divided by the initial length of the material. Strain is usually measured with a strain gauge, which typically consists of a thin foil wire on a flexible backing that is attached to the material being measured with an adhesive. As the foil is deformed, the resistance of the wire changes, with decreasing resistance under compression and increasing resistance under tension. Strain gauges are very sensitive devices that can measure down to the microstrain level. They are often used as the sensing element in load cells and scales.

Strain gauges are typically used in a bridge circuit that convert the change in resistance to a voltage. The configuration of the bridge can also be used to increase the sensitivity of the measurement using multiple gauges, or for temperature compensation. The disadvantages of strain gauges are that they are fragile if not protected, and the installation requires a clean, smooth surface for mounting. Stain gauges are typically powered by DC voltage, but they also work with AC power.

Strain measurement can also be accomplished with fiber Bragg grating sensors, but the devices are still very costly and have limited availability. They require much more complicated external units than traditional strain gauges. However, they may be more rugged in the long term than traditional strain gauges.

Applications of Strain Sensors

Strain gauges could be used to identify when structural members of towers were plastically deformed by severe weather or other events that caused excessive loading. The strain gauges would need to be applied directly to the structural members being measured. The most important of these structural members would likely be at the base of the tower, requiring the sensors and associated electronics to be located near the base of the tower.

It is likely that tilt sensor data could provide similar insight to strain gauge data, with easier installation and improved ruggedness. Additionally, the tilt sensor would be located at the top of the tower rather than the bottom of the tower, making it possible to co-locate the tilt sensor with other proposed sensors.

Summary of Strain Gauges	
Commercial technology options	Foil or semiconductor strain gauges.
Expected improvements over next 20 years	Further development of fiber bragg grating strain gauges for lower cost applications.
Physical interface requirements	Must be physically mounted to structural members at clean, smooth locations.
Power requirements	Typically a few milliwatts.
Data/bandwidth	As needed. Continuous monitoring not required.
Size/weight	Very small and lightweight. Foil strain gauges can be a fraction of an inch and weigh a few ounces.

3.1.9 Tilt Sensing

Tilt sensors are typically fluid, electrolytic, pendulum, or solid state devices. Electrolytic and fluid-based tilt sensors are inexpensive, but do not have the reliability of solid state devices. Solid state tilt sensors use silicon micro-machined capacitive sensors to detect the orientation of the acceleration due to gravity. They function similarly to capacitive MEMS accelerometers, but include integrated electronics to calculate the inclination angle based on the dc accelerations measured and output a signal proportional to the calculated angle. Solid state tilt sensors are rugged, inexpensive devices that can be purchased in sealed packages.

Applications of Tilt Sensors

Tilt sensors can be used on transmission line towers to calculate the tilt angle of the tower and determine if the tower has been overloaded or has been damaged during a severe weather event. For maximum effectiveness, the tilt sensor should be mounted near the top of the tower. A dual-purpose, multi-axis accelerometer could be employed for this purpose, as long as the accelerometer could measure DC acceleration levels. However, external electronics to calculate the inclination angle based on the measured accelerations would need to be used. Such electronics are pre-packaged in off-the-shelf tilt sensors.

Summary of Tilt Sensors	
Commercial technology options	Fluid, electrolytic, pendulum, or solid state.
Expected improvements over next 20 years	Higher sensitivity, smaller form factor, lower power requirements.
Physical interface requirements	Must be mounted directly to the tower, preferably near the top.
Power requirements	20–100 mW, DC input voltage.
Data/bandwidth	As needed. Continuous monitoring not required.
Size/weight	Small and lightweight. Typically 1″ cube weighing a few ounces.

3.1.10 Magnetostrictive Sensing (MsS)

Magnetostrictive sensor (MsS) technology is a method of generating ultrasonic guided waves into a material that can travel over a long range to detect changes in material cross section. Guided waves refer to mechanical (or elastic) waves in ultrasonic and sonic frequencies that propagate in a bounded medium (such as pipe, plate, rod, etc.) parallel to the plane of its boundary. The wave is termed "guided" because it travels along the medium guided by the geometric boundaries of the medium.

Since the wave is guided by the geometric boundaries of the medium, the geometry has a strong influence on the behavior of the wave. In contrast to ultrasonic waves used in conventional ultrasonic inspections that propagate with a constant velocity, the velocity of guided waves varies significantly with wave frequency and geometry of the medium. In addition, at a given wave frequency, guided waves can propagate in different wave modes and orders.

Although the properties of guided waves are complex, with judicious selection and proper control of wave mode and frequency, guided waves can be used to achieve 100-percent volumetric inspection of a large area of a structure from a single sensor location.

The MsS, developed and patented by SwRI, is a sensor that generates and detects guided waves electromagnetically in the material under testing. For wave generation, it relies on the magnetostrictive (or Joule) effect; the manifestation of a small change in the physical dimensions of ferromagnetic materials—on the order of several parts per million in carbon steel—caused by an externally applied magnetic field. For wave detection, it relies on the inverse-magnetostrictive (or Villari) effect; the change in the magnetic induction of ferromagnetic material caused by mechanical stress (or strain). Since the probe relies on the magnetostrictive effects, it is called a "magnetostrictive sensor (MsS)." This is illustrated as follows.

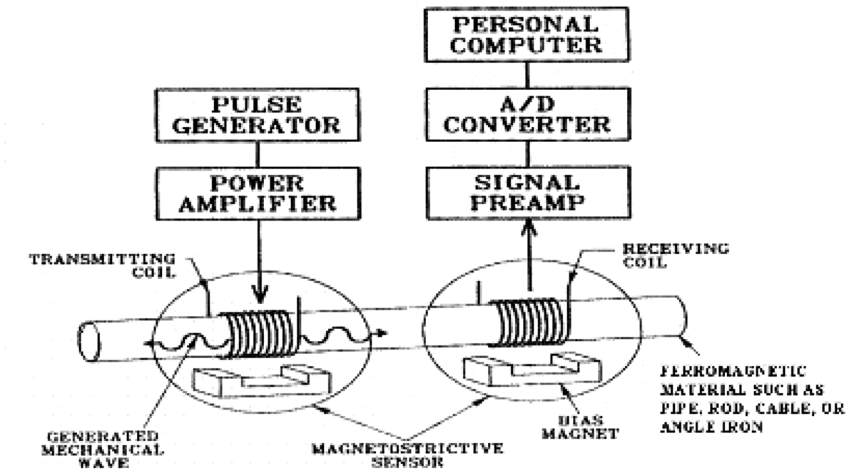


Figure 3-3
Illustration of the MsS Guided Wave Technology Showing Transmission and Receiving

In practice, the transmitted coil and receiver coil are the same or at least co-located.

A schematic diagram is illustrated below of the MsS and associated instruments (Model MsSR3030) for generation and detection of guided waves. The sensor is configured to apply a time-varying magnetic field to the material under testing and to pick up magnetic induction changes in the material caused by the guided wave. For ferromagnetic cylindrical objects (such as rods, tubes, or pipes), the MsS is ring-shaped and utilizes a coil that encircles the object. For plate-like objects, the MsS is rectangular-shaped and utilizes either a coil wound on a U-shaped core or a flat coil. If the component is not ferromagnetic, a thin ferromagnetic strip can be bonded to the part and the guided wave is then generated in the ferromagnetic strip which is then coupled into the part being inspected.

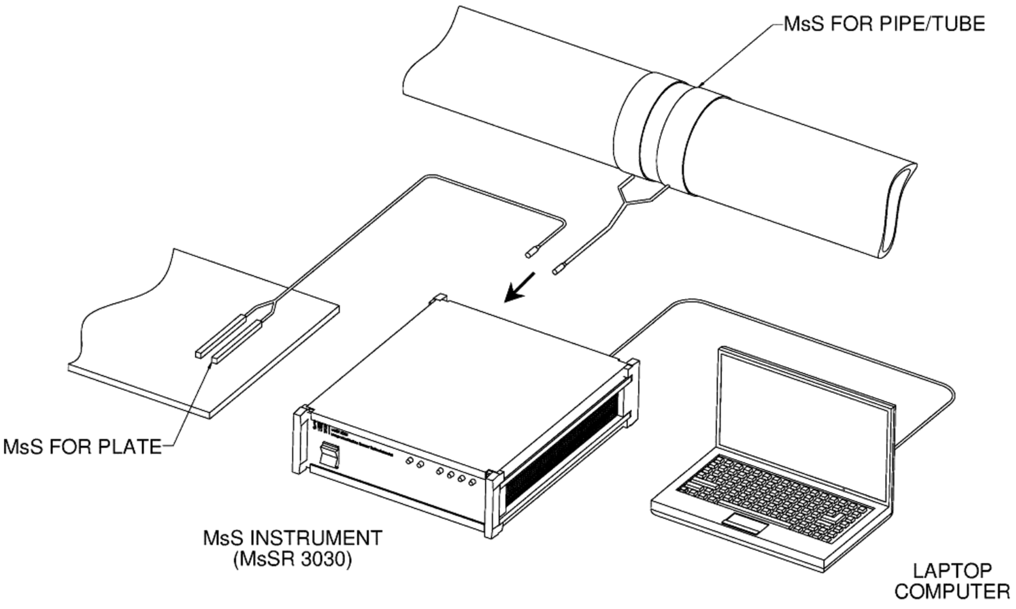


Figure 3-4
A Single MsS Generates and Detects Guided Waves Propagating in Both Directions

In practical inspection applications, the guided wave generation and detection are controlled to work primarily in one direction so that the area of the structure on either side of the sensor can be separately inspected. The wave direction control is achieved by employing two sensors, as illustrated above, and the phased-array principle of the MsS instrument.

For operation, the MsS requires that the ferromagnetic material under testing be in a magnetized state. This is achieved by applying a DC bias magnetic field to the material using either a permanent magnet, electromagnet, or residual magnetization induced in the material. The DC bias magnetization is necessary to enhance the transduction efficiency of the sensor (from electrical to mechanical and vice versa) and to make the frequencies of the electrical signals and guided waves the same.

Technical features of the MsS include the following:

- Electromagnetic guided wave generation and detection—Requires no couplant and is capable of operating with a substantial gap to the material surface
- Good sensitivity in frequencies up to a few hundred kHz—Ideal for long-range guided-wave inspection applications.

The MsS is directly operable on structures made of ferrous materials such as carbon steel or alloyed steel. The MsS is also operable on structures made of nonferrous materials, such as aluminum, by bonding a thin layer of ferromagnetic material (typically nickel) to the structure under testing or inspection and placing the MsS over the layer. In the latter case, guided waves are generated in the ferromagnetic layer and coupled to the nonferrous structure. Detection is achieved through the reverse process. This technology is applicable for monitoring structures.

In long-range guided wave inspection and monitoring, a short pulse of guided waves in relatively low frequencies (up to a few hundred kHz) is launched along the structure under inspection, and signals reflected from geometric irregularities in the structure such as welds and defects are detected in the pulse-echo mode, as schematically shown below. From the time to the defect signal and the signal amplitude, the axial location and severity of the defect are determined.

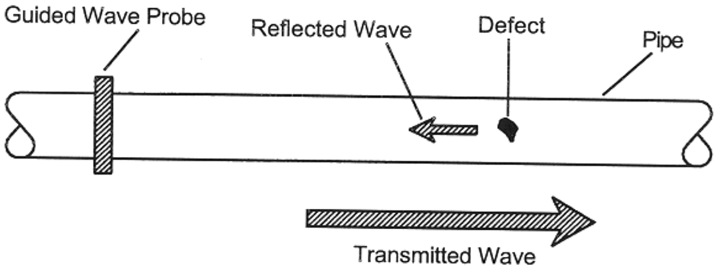


Figure 3-5
MsS Wave Reflected by a Defect in a Pipe

The typically achievable inspection range from one sensor location is more than 30 m in bare pipe and more than 10 m in bare plate. Within the inspection range, the cross-sectional area of detectable defect size using the MsS is typically 2 to 3 percent of the total pipe-wall cross section in pipe and rod diameter in rod. In plates, it is typically 5 percent of the guided wave beam size or larger.

Because of the long-inspection range and good sensitivity to defects, guided-wave inspection technology such as MsS is very useful for quickly surveying a large area structure for defects, including areas that are difficult to access from a remotely accessible location.

Applications of MsS

MsS technology has been applied for inspection of suspender ropes on highway suspension bridges and piping and heat exchanger tubes in refineries and chemical plants. For the power line industry, MsS has been applied to the detection of corrosion in steel poles and transmission tower anchor rods. Some recent work has been done that indicated that MsS could monitor long lengths of continuous metal with bolt holes and detect loosened bolts. This needs further work to harden the technology. In addition, some work has been done to look at the lattice structure buried in concrete. More work is needed. In addition, recent work has also been done on MsS inspection of ASCR cable with some success. All these applications presently require the MsSR instrument (about the size of a laptop) that can be battery operated (12 VDC) or 110V/220V.

Summary of MsS	
Commercial Technology options	Technology already being used in manned applications in power industry for anchor rods, steel poles, transmission towers, ACSR
Expected improvements over next 20 years	The instrumentation will get much smaller, have embedded microprocessors to collect and analyze data, and will incorporate wireless communication technology
Physical interface requirements	
Power requirements	Operable from 12 VDC or 110/220 AC, 330 Vpp max at 40 App max for 2 cycles (at 32 KHz for 32 μs up to 250 KHz for 4 μs)
Data/bandwidth	11–54 MBits/sec
Size/weight	11.5″ by 14.5″ by 4″ at 10 lbs …but will be reduced to 5″ by 5″ by 1″ at 2 lbs someday

3.1.11 Ultrasonic Sensing

Ultrasonic testing is based on time-varying deformations or vibrations in materials, which is generally referred to as acoustics. In solids, sound waves can propagate in four principle modes that are based on the way the particles oscillate. Sound can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves. Compression waves can be generated in liquids, as well as solids because the energy travels through the atomic structure by a series of comparison and expansion (rarefaction) movements. Longitudinal and shear waves are the two modes of propagation most widely used. However, guided wave modes can also be generated in which the wave that propagates is controlled by the geometry of the part in which the wave is propagating. These waves include plate waves, Lamb waves and others. Plate waves can only be generated in thin metal plates. Lamb waves are the most commonly used plate waves in NDT (non destructive testing). Lamb waves are complex vibration waves that travel through the entire thickness of a material. Propagation of Lamb waves depends on the density and the elastic material properties of a component. They are also influenced a great deal by the test frequency and material thickness.

Ultrasonic waves are most often generated with piezoelectric transducers made from piezoelectric ceramics. The conversion of electrical pulses to mechanical vibrations and the conversion of returned mechanical vibrations back into electrical energy is the basis for ultrasonic testing. A number of variables will affect the ability of ultrasound to locate defects. These include the pulse length, type and voltage applied to the crystal, properties of the crystal, backing material, transducer diameter, and the receiver circuitry of the instrument.

Applications of Ultrasonics

The most common application of ultrasonics is to test for thickness (detecting loss of material caused by corrosion) using 0 degree, inspection for cracks near the location of the transducers (using angle beam), and detecting defects over a long range using guided waves. However, one major drawback to ultrasonics is the requirement to have the transducer coupled to the part.

Potential field applications for tower inspection and monitoring include monitoring for cracks and corrosion in the lattice tower structure and inspecting anchor rods for corrosion (the anchor rods must be greater than 1½ inch in diameter).

Summary of Ultrasonic Sensing	
Commercial Technology options	Technology already being used in manned applications in power industry for anchor rods and transmission towers.
Expected improvements over next 20 years	The instrumentation will get much smaller, have embedded microprocessors to collect and analyze data, and will incorporate wireless communication technology.
Physical interface requirements	
Power requirements	Operable from 12 VDC or 110/220 AC, (at 32 KHz for 32 μs up to 250 KHz for 4 μs)
Data/bandwidth	11–54 MBits/sec
Size/weight	Can be as small as 5″ by 5″ by 1″ at 2 lbs but will get even smaller in the future.

3.1.12 *Electromagnetic-Acoustic Transducer (EMAT)*

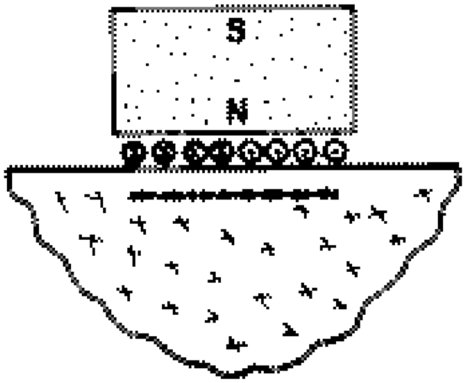
Electromagnetic-acoustic transducers (EMAT) generates ultrasonic waves in materials through totally different physical principles than piezoelectric transducers and do not need couplant. When a wire is placed near the surface of an electrically conducting object and is driven by a current at the desired ultrasonic frequency, eddy current will be induced in a near surface region of the object. If a static magnetic field is also present, these eddy currents will experience Lorentz forces of the form

$$\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B},$$

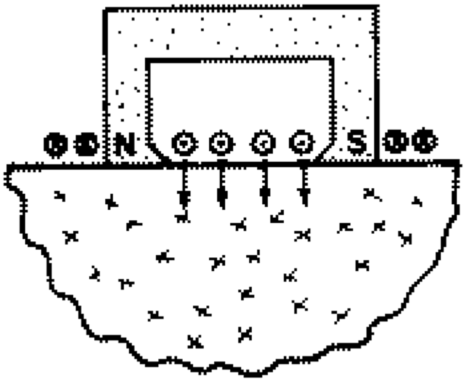
where $\boldsymbol{F}$ is the body force per unit volume, $\boldsymbol{J}$ is the induced dynamic current density, and $\boldsymbol{B}$ is the static magnetic induction.

The most important application of EMAT has been in nondestructive evaluation (NDE) applications such as flaw detection or material property characterization. Couplant free transduction allows operation without contact at elevated temperatures and in remote locations. The coil and magnet structure can also be designed to excite complex wave patterns and polarizations that would be difficult to realize with fluid coupled piezoelectric probes.

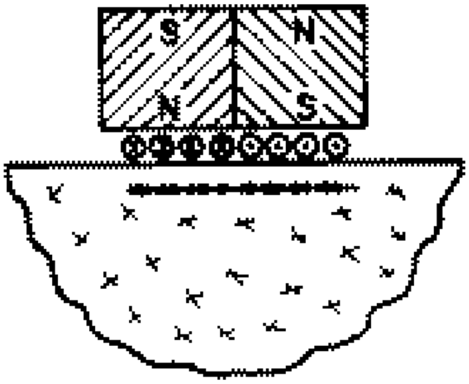
A number of practical EMAT configurations are shown below. In each, the biasing magnet structure, the coil, and the forces on the surface of the solid are shown in an exploded view. The first three configurations excite beams propagating normal to the surface and produce beams with radial, longitudinal, and transverse polarizations, respectively. The final two use spatially varying stresses to excite beams propagating at oblique angles or along the surface of a component. Although a great number of variations on these configurations have been conceived and used in practice, consideration of these three geometries serves to introduce the fundamentals.



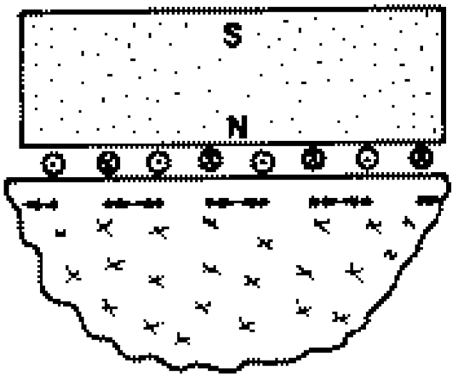
Cross-sectional view of a spiral coil EMAT exciting radially polarized shear waves propagating normal to the surface.



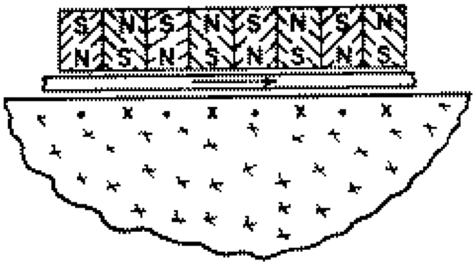
Cross-sectional view of a tangential field EMAT for exciting polarized longitudinal waves propagating normal to the surface.



Cross-sectional view of a normal field EMAT for exciting plane polarized shear waves propagating normal to the surface.



Cross-sectional view of a meander coil EMAT for exciting obliquely propagating L or SV waves, Rayleigh waves, or guided modes (such as Lamb waves) in plates.



Cross-sectional view of a periodic permanent magnet EMAT for exciting grazing or obliquely propagating horizontally polarized (SH) waves or guided SH modes in plates.

Practical EMAT designs are relatively narrowband and require strong magnetic fields and large currents to produce ultrasound that is often weaker than that produced by piezoelectric transducers. Rare-earth materials such as Samarium-Cobalt and Neodymium-Iron-Boron are often used to produce sufficiently strong magnetic fields, which may also be generated by pulsed electromagnets.

EMAT offers many advantages based on its couplant-free operation. These advantages include the abilities to operate in remote environments at elevated speeds and temperatures, to excite polarizations not easily excited by fluid coupled piezoelectrics, and to produce highly consistent measurements. These advantages are tempered by low efficiencies, and careful electronic design is essential to applications. EMAT is also more expensive than piezoelectric transducers.

Application of EMAT

EMAT is most often used in high temperature applications of ultrasonics or where not couplant is allowed for 0 degree wall thickness and angle beam inspection for cracks. EMAT can also be used to generate guided waves in plate structure such as lattice towers. There do not appear to be EMAT applications for long range monitoring of piping, tubing or rods, however, it could be used for those applications with some development.

EPRI is developing an EMAT technique to inspect broken conductor strands where the strands may be internal to the conductor or hidden under other components such as an armor rod or a conductor shoe. Consideration is also being given to inspecting compression connectors. **Figure 3-6** shows the application of the EPRI developed EMAT technology under energized conditions to identify broken strands.

Figure 3-6
Energized Implementation of EPRI EMAT Device to Inspect for Broken Srands Internal to the Conductor Shoe

Summary of EMAT	
Commercial Technology options	Technology already being used in manned applications to identify broken strands on transmission lines as well as in piping in power generation plants
Expected improvements over next 20 years	The instrumentation will get much smaller, have embedded microprocessors to collect and analyze data, and will incorporate wireless communication technology
Physical interface requirements	
Power requirements	110/220 AC,
Data/bandwidth	11–54 MBits/sec
Size/weight	Larger than piezoelectric instruments and more expensive

3.1.13 Eddy Current Sensing

Eddy current inspection is one of several NDT methods that use the principal of “electromagnetism” as the basis for conducting examinations. Several other methods such as Remote Field Testing (RFT), Flux Leakage and Barkhausen Noise also use this principle.

Eddy currents are created through a process called electromagnetic induction. When alternating current is applied to the conductor, such as copper wire, a magnetic field develops in and around the conductor. This magnetic field expands as the alternating current rises to maximum and collapses as the current is reduced to zero. If another electrical conductor is brought into the close proximity to this changing magnetic field, current will be induced in this second conductor. Eddy currents are induced electrical currents that flow in a circular path. They get their name from "eddies" that are formed when a liquid or gas flows in a circular path around obstacles when conditions are right.

One of the major advantages of eddy current as an NDT tool is the variety of inspections and measurements that can be performed. In the proper circumstances, eddy currents can be used for

1. Crack detection
2. Material thickness measurements
3. Coating thickness measurements
4. Conductivity measurements for:
   a. Material identification
   b. Heat damage detection
   c. Case depth determination
   d. Heat treatment monitoring

Some of the advantages of eddy current inspection include being sensitive to small cracks and other defects, detecting surface and near surface defects, immediate results, portable equipment, minimum part preparation, non-contact test probe, and the ability to inspect complex shapes and sizes of conductive materials.

Some of the limitations of eddy current inspection include: only conductive materials can be inspected, the surface must be accessible to the probe, the skill and training required is more extensive than other techniques, surface finish and roughness may interfere, reference standards are needed for setup, depth of penetration is limited, and flaws such as delaminations that lie parallel to the probe coil winding and probe scan direction are undetectable. Usually the eddy current probe has to be moved over the part or placed over a part that is changing with time.

Applications of Eddy Current Sensing

Eddy current is used in a wide range of applications for the power and aerospace industries for detection of cracks and corrosion. Present eddy current sensing technology could be used to measure corrosion depth and detect/size cracking in lattice towers.

Summary of Eddy Current Sensing	
Commercial Technology options	Technology already being used in manned applications in power industry piping
Expected improvements over next 20 years	The instrumentation will get much smaller, have embedded microprocessors to collect and analyze data, and will incorporate wireless communication technology
Physical interface requirements	
Power requirements	110/220 AC,
Data/bandwidth	11–54 MBits/sec
Size/weight	Larger than piezoelectric instruments and more expensive

3.1.14 Ground Penetrating Radar

Ground penetrating radar (GPR) is a nondestructive geophysical method that produces a continuous cross-sectional profile or record of subsurface features, without drilling, probing, or digging. GPR profiles are used for evaluating the location and depth of buried objects and to investigate the presence and continuity of natural subsurface conditions and features. GPR operates by transmitting pulses of ultra high frequency (UHF) radio waves down into the ground via a transducer or antenna. The transmitted energy is reflected from various buried objects or distinct contacts between different earth materials. The antenna then receives the reflected waves and stores them as an image. GPR performance is highly dependent upon soil conditions. Visibility is typically 10–12 feet deep in sandy conditions such as in Florida, however heavy clay conditions are common and limit visibility to just a few feet.

GPR could be applied to foundation inspections of grillage at tower sites. GPR image baselines would need to be established at tower sites, and then periodic imaging could be performed in order to look for changes that signify the need for further investigation. Discussions with GPRS, a company that provides GPR services (not an equipment manufacturer) indicate that the equipment costs on the order of $30k, weighs about 50 lbs, is the size of a small baby cart, and operates from rechargeable lithium-ion battery packs.

Since it does not appear to be cost effective to dedicate GPR equipment at every tower site and/or automate it, this technology is presently not well suited to the instrumented tower concept, but could be nonetheless applied manually for sites that have foundation integrity concerns.

3.1.15 Proximity Sensing

The purpose of a proximity gauge is to determine when an object approaches the location of the gauge. Proximity gauges use a number of different technologies including inductive, capacitive, optical, and ultrasonic. Inductive sensors work only with metal objects, the material and size of which must be known so that measurements can be carried out with sufficient precision (reducing factor). Inductive sensors mounted immediately adjacent to one another will affect one another, since the vision range of each sensor is 180°. Static and dynamic magnetic fields disturb the function of the sensor, and measurement precision fluctuates with temperature. With capacitive sensors, the object always serves as an intentional second capacitor plate and so both the material and size of the object must be known in order to reliably measure the distance to the sensor. In addition, measurement precision is affected by relative humidity, temperature, and electromagnetic fields. Optical sensors can be used only to a limited extent in an industrial environment, since they can no longer be guaranteed to work properly in dirty conditions. The measurement precision of ultrasound sensors depends very largely on the ambient conditions, e.g., air humidity and temperature. Some examples are described below. Airborne ultrasonics are used to locate objects in the field of view of the ultrasonic sensors.

The optical technology usually consists of a light beam transmitted to a photo-electric receiver. When the light beam is transmitted, the electronic circuit works in a good state. When the beam is disturbed or broken, the electronic circuit is changes. This technology is used in garage door openers to prevent injury to a person that might be in the way of the garage door closing and in customer counting as a door opens or someone passes through a door. These are inexpensive but usually require a transmit and receive location. Fiber optics can also be incorporated into the design.

In the capacitive approach, an electronic circuit with a capacitive field is established and the object or person that approaches changes the capacitance of the circuit.

In the eddy current proximity technology, a coil in an oscillator circuit generates a high-frequency electromagnetic alternating field. This field is emitted at the sensing face of the sensor. If a metallic object (switching trigger) nears the sensing face, eddy currents are generated. The resultant losses draw energy from the oscillating circuit and reduce the oscillations. The signal evaluator behind the LC oscillating circuit converts this information into a clear signal.

For the infrared technique, an infrared detector is used to detect the heat of an object or body approaching the sensor location. Most of these technologies have a limited field of view.

Applications of Proximity Sensing

Proximity sensors are used in all kinds of applications. Breaking optical beams is a standard technique for counting as well as intrusion sensing. Changing the electronic circuit capacitance is used for intrusion detection. Airborne ultrasonics is used to monitor objects close to a car as it is backing up. These could all be used in some form for monitoring around transmission towers.

Summary of Proximity Sensing	
Commercial Technology options	Technology already being used in many commercial applications from garage door openers to counting systems
Expected improvements over next 20 years	The instrumentation will get much smaller, have embedded microprocessors to collect and analyze data, and will incorporate wireless communication technology
Physical interface requirements	Flexible, remote sensing options
Power requirements	Battery operable
Data/bandwidth	1 bit of information 1 second update rate may be adequate for tower tampering detection alarm
Size/weight	Relatively small and light

3.1.16 Voltage Potential and Half Cell Measurement

Corrosion is the destructive attack of a material by reaction with its environment. Corrosion control is achieved by recognizing and understanding corrosion mechanisms. When metal is placed in the earth, a natural galvanic or corrosion cell is formed. When it is important to mitigate corrosion, metal components are usually galvanized or coated with an isolating coating such as epoxy, paint, or tar. However, often the coatings degrade or fail, so it is important to understand the corrosive environment of the soil and the metal. To measure the corrosion potential of a localized soil region, a Wenner four-pin instrument is commonly used. The measurement is made by placing four pins in the soil in a line at equal distances from each other. A current is sent through the two outer pins. By measuring the voltage across the two inner pins, the soil resistance can be calculated using Ohm's Law (V=IR). Soil resistivity is given by

$$\text{Resistivity} = 191.5\ RL\ \text{(ohm-cm)},$$

where R is the resistance found above ground and L is the pin spacing in feet. The measurement is affected by the presence of buried metal. Usually, as soil resistivity decreases, the corrosivity increases.

Applications of Voltage Potential and Half Cell Measurement

EPRI Solutions Inc., developed and field tested a suitable inspection tool capable of identifying the level of corrosion activity, the rate of corrosion and the expected remaining service life without requiring the excavation of the direct embedded steel components. The inspection tool utilizes 'half cell' measurement technology and integrated software combined in a field hardened, battery powered case weighing less than five pounds. [Reference *Ground line corrosion damage activity and damage assessment for direct embedded steel structures and guy anchors,* Ostendorp, M., Transmission and Distribution Construction, Operation and Live-Line Maintenance, 2003. 2003 IEEE ESMO. 2003 IEEE 10th International Conference on 6–10 April 2003 Page(s): 78–86].

Larson discussed corrosion due to electrochemical reactions and methods for dealing with it for electrical system components. To estimate the rates of substation ground grid and guy anchor corrosion, four tests are suggested, namely: (1) earth resistivity (2) guy current, (3) grid-to-earth potential; and (4) polarizing current. In his paper, an analysis of test results is provided showing the degree of corrosion and the form of correction that is necessary. [Reference *Problems and detection of line anchor and substation ground grid corrosion,* Lawson, V.R., Industry Applications, IEEE Transactions on Volume 24, Issue 1, Jan/Feb 1988 Page(s):25–32].

Once the corrosion potential has been determined, a current can be put into the ground to counter the corrosion process. For larger structures, **Impressed Current Cathodic Protection** (**ICCP**) systems are used. These systems use anodes connected to a DC power source (a cathodic protection rectifier). Anodes for ICCP systems are tubular and solid rod shapes or continuous ribbons of various specialized materials. These include high silicon cast iron, graphite, mixed metal oxide, platinum and niobium coated wire and others. An example of an impressed current cathodic protection system is shown below.

Figure 3-7
Cathodic Protection Rectifier Connected to a Pipeline

A typical ICCP system for a pipeline would include an AC powered rectifier with a maximum rated DC output of between 10 and 50 amperes and 50 volts. The positive DC output terminal is connected via cables to the array of anodes buried in the ground (the anode ground bed). For many applications the anodes are installed in a 60 m (200 foot) deep, 25 cm (10-inch) diameter vertical hole and backfilled with conductive coke (a material that improves the performance and life of the anodes). A cable rated for the expected current output connects the negative terminal of the rectifier to the pipeline. The operating output of the rectifier is adjusted to the optimum level by a CP expert after conducting various tests including measurements of electrochemical potential. This technology might be useful for grillage or other buried electrical component.

Summary of Voltage Potential and Half Cell Measurement
Commercial Technology options
Expected improvements over next 20 years
Physical interface requirements
Power requirements
Data/bandwidth
Size/weight

3.1.17 Radio Frequency Interference Sensing

Partial Discharge (PD) in high voltage system components is a concern because it degrades component material and can lead to catastrophic mechanical failure. PD produces Radio Frequency Interference (RFI) that is detectable using electronic radio signal receivers. PD emissions at radio frequencies (in the MHz range) can be demodulated to the audio band and heard as distinctive bursts of crackling. Radar Engineers of Portland, OR, makes products that are geared specifically to detect PD in electric power utility applications. Their Model 246 “EMI Sniffer” is a handheld device with a simple bar meter display, audio speaker, and gain control. Their Model 70 is designed to attach to the end of a hotstick and is marketed for use in live line evaluation of splices, elbows, and junction modules. Radar Engineers also sells a line of products for locating television interference (TVI), which is often caused by sparking hardware on power lines. These products (Models 240A, 242, M330, 245, and 247B) work similarly to the aforementioned products but are generally more comprehensive and use directional antennas to assist in pinpointing problem components. EPRI and SwRI are presently surveying RFI detection methods and utility procedures for identifying failing porcelain insulators in transmission systems. EPRI and SwRI have broached Radar Engineers about a potential product development tailored specifically to this application and the automatic detection of problems without reliance on a trained operator. Radar Engineers has expressed interest. EPRI also has a separate on-going development to locate PD in substations using multiple antennas and a wide bandwidth multi-channel oscilloscope to capture emissions, and then signal processing algorithms to analyze the data, correlate PD events, and estimate PD location based on the time of signal arrival from the different known antenna locations.

With these known products and on-going developments, it appears that RFI sensing could be integrated into the instrumented tower concept. In the short term, existing Radar Engineers products could be used. In the longer term, automated solutions may be available.

Summary of RFI Sensing	
Commercial Technology options	Several products available from Radar Engineers, Portland, OR.
Expected improvements over next 20 years	Automated detection without need for operator interpretation and associated training.
Physical interface requirements	Remote sensing. Pinpointing the problem to a particular component is a challenge.
Power requirements	Flexible, battery operated available.
Data/bandwidth	Low if processing done at sensor, otherwise can be very high.
Size/weight	Flexible, handheld available.

3.1.18 Leakage Current Sensing

Leakage current peaks flowing through high-voltage insulators can be monitored as an indicator of the insulator contamination level, for example, that due to pollution buildup. Insulator maintenance to wash the insulators is required when contamination levels are high in order to mitigate the potential for flashover. Flashover events are undesirable, resulting in system outages and an increased risk of future catastrophic mechanical failure. Leakage current sensing may also be applied to transmission line surge arresters which are becoming more prevalent in transmission systems and have similar concerns for pollution buildup leading to flashover events.

EPRI has developed at SwRI a leakage current sensor that is designed to address this concern. The sensor continuously monitors the leakage current peak level and stores a histogram of bin counts indicating the number of peaks that exceed programmed thresholds. The sensor incorporates either a custom split-core current transformer (CT) for clamp-around applications, or a commercial toroidal CT product for in-line applications. It is attached to the grounded side of the insulator to reduce high-voltage safety and interference concerns. The sensor is estimated to operate for more than 18 years using two D-size 3.6V Lithium Thionyl Chloride batteries. Radio backscatter is used to communicate the sensor result (i.e., bin counts) to a reader. The reader can pick up sensor readings at standoff ranges out to a few hundred feet and from a moving platform such as a vehicle or helicopter. Remaining challenges to address are packaging/commercialization for competitive pricing, and verification of the calibration accuracy over long periods of time. The EPRI leakage current sensor appears to be an excellent candidate for the instrumented tower concept.

Summary of Leakage Current Sensing	
Commercial Technology options	None presently identified, but EPRI development is leading towards commercialization
Expected improvements over next 20 years	Power harvesting (solar, etc) could extend life indefinitely beyond practical battery limits
Physical interface requirements	Clamp-around versus in-line configurations; secure mounting to grounded side of component
Power requirements	2.5V at 250 μA
Data/bandwidth	11 byte data payload; read once per hour at most, once per month at least
Size/weight	8.2″ x 6.2″ x 1.6″, approx 4 lbs

3.1.19 Direct Contact Temperature Sensing

The temperature of transmission line splices can be monitored as an indicator of excessive resistance, which could lead to catastrophic mechanical failure due to thermal stress. A marginally bad splice may become a critical risk in the future as consumer demand and line loading increases over the years exacerbate the thermal problem. Fly-by inspections commonly use infrared temperature sensing to identify overheated splices, but this is not a definitive approach because a) splice emissivity is uncontrolled and can vary significantly due to contamination buildup on the splice, b) operator interpretation of the thermal image is required, and c) the temperature rise depends on the line current which is typically not known.

EPRI has developed at SwRI a splice temperature sensor that is designed to address this concern. The sensor uses a thermocouple to directly monitor the surface temperature of the splice. The sensor incorporates a coil to harvest power from the magnetic field generated by the line current. Besides the advantage of batteryless operation, the coil voltage is also monitored to provide a measure of the line current amplitude. The sensor reports the latest temperature measurement and associated current, as well as the peak temperature and associated current at the time of the peak. Radio backscatter is used to communicate these sensor results to a reader. The reader can pick up sensor readings at standoff ranges out to a few hundred feet and from a moving platform such as a vehicle or helicopter. Remaining challenges to address are packaging/commercialization for competitive pricing, and verification of the calibration accuracy over long periods of time. The EPRI splice temperature sensor appears to be an excellent candidate for the instrumented tower concept. In addition to splices and conductors, the same concept can be applied to other components that may have overheating concerns (e.g., disconnect switches, separable connectors).

Summary of Direct Contact Temperature Sensing	
Commercial Technology options	EPRI development is leading towards commercialization; similar commercial up starts are marketed but availability is uncertain
Expected improvements over next 20 years	Packaging costs should decrease with time and quantities
Physical interface requirements	Direct contact to splice or conductor
Power requirements	2.5V at 500 μA peak, <50 μA average
Data/bandwidth	5 byte data payload; read once per hour at most, once per month at least
Size/weight	6″ x 2.5″ x 3.5″ sensor, 5″ x 5.5″ x 1″ attachment clamp, Approximately 4 lbs. total

3.1.20 Lightning Strike Sensing

Lightning strikes are commonly experienced at transmission towers due to the height of the grounded steel structures and open rural locations. Lightning strikes may cause critical mechanical damage, therefore it is desirable to count strikes at a particular structure and inspect it more closely if lightning strikes have been sensed.

Commercial products exist. Polyphaser of Minden, Nevada, has a Model LSC-13 Lightning Strike Counter that connects as a shunt across a section of the grounded structure or wire where current from a strike is expected to flow. The unit's sensitivity increases as the separation is increased between the shunt sense leads. It has a mechanical counter that counts up to 999,999 before resetting to zero. The Model LSC-13 also has a dry contact closure that can be externally monitored by an electronic circuit to automatically detect the strike and energy amplitude (which is a function of contact closure duration). The unit operates from a 9V battery. This is just one example found, many other products and options may exist.

Summary of Lightning Strike Sensing	
Commercial Technology options	Polyphaser Model LSC-12, LSC-13; May be many others
Expected improvements over next 20 years	No insight available
Physical interface requirements	Direct contact to structure; Requires several feet of spacing between sense leads for high sensitivity
Power requirements	9V battery
Data/bandwidth	Few bytes, approx once per month
Size/weight	5″ x 4″ x 2″, Estimate 1–2 lbs. max

3.2 Data Communications Technology

Sensor readings must be communicated to hubs and then to a central location so that maintenance actions can be ascertained/prioritized and results archived for future reference. A number of data communications technologies are considered for this application. Technologies are covered by frequency spectrum, radio frequency (RF), then optical because of their vastly differing implementations. The dividing line in the spectrum between RF and optical is typically considered about 300 GHz. Both RF and optical technologies are in widespread use for data communications.

Candidate data communications technologies are addressed, organized as follows:

1. RF Wireless Line of Sight Transceiver Technology
2. RF Wireless Backscatter Technology
3. RF Wireless Over-the-Horizon Technology
4. Infrared Wireless Technology
5. Fiber Optic Technology
6. Free Space Optical Technology
7. Data Communications Over Power Lines

Due to the trades in communication range, data rate, cost, power consumption, device size, and diversity of commercial product availability, RF wireless line-of-sight (LOS) transceiver technologies receive the most discussion in this report. Technologies in this family include communications IEEE 802 standards such as ZigBee and WiFi, as well as proprietary radios and radio modules. Other technologies are summarized, including RF backscatter, RF over-the-horizon (OTH), optical wired, optical wireless, and data communications over power line. A brief summary is provided for each along with an assessment of the technology's application to the instrumented tower concept, followed by a table that identifies the performance characteristics of the technology.

The purpose of this report is not to select a single communications technology, but to provide insight into the tradeoffs that exist between the different choices. The system in theory can support many different communication technologies so long as there is a common data language/format/protocol in the end.

3.2.1 RF Wireless Line of Sight (LOS) Transceiver Technology

RF wireless LOS technology encompasses a vast range of technologies and commercially available products. Commercially available RF LOS radios directed at the consumer data communications markets use radio frequency waves in the Ultra High Frequency (UHF, 300 MHz to 3 GHz) to low Super High Frequency (SHF, 3 GHz to 30 GHz) frequency bands. This discussion focuses on commercial products below 6 GHz because higher frequency microwave devices are highly directional, expensive, and target broadcasting and telecommunications markets. Further, this discussion omits cellular mobile phone technology because it is not yet targeting low-cost, networked transfer for raw data, although the trend toward broadband Internet might have interesting applications in the future.

RF LOS radios can be generally considered in two categories: those supported by an industry standard and those that are not. The Institute of Electrical and Electronics Engineers (IEEE) defines many of these standards in the family of IEEE 802 standards for Local Area Networks (LANs) and Metropolitan Area Networks (MANs). A number of non-standardized communications technologies are suitable for SCADA and monitoring/control applications.

IEEE 802 Standard Technologies

Standardized communication technologies under consideration include the 802.11 series, commonly referred to as Wi-Fi; the 802.15 series, which includes Bluetooth and ZigBee; the 802.16 series, commonly referred to as WiMAX; and the 802.20 series, which is known as Mobile Broadband Wireless Access (MBWA) or Mobile-Fi. Each is summarized in **Table 4** below. Off-the-shelf modules and chipsets are available for most. However, integration of chipsets into a custom solution typically requires additional levels of effort due to the complicated communications protocols.

Wi-Fi, Bluetooth, and ZigBee are candidates for sensor to tower or intra-tower communication. Wi-Fi technology supports higher data rate sensors at the cost of higher power consumption and larger size. Range extenders for Wi-Fi exist, making it possible for tower-to-tower communication. Integration of a Wi-Fi network, however, entails integration of a complicated network architecture. Bluetooth is suitable for communication of low data rate sensor data. The range of Bluetooth is severely limited, and although longer range (300 foot) Bluetooth Class 1 modules exist, the trend in Bluetooth is toward the shorter-range (10s of feet) Class 2 devices. Bluetooth modules have an advantage of being small and low power, but integration into a system is complicated by its master-slave topology. ZigBee technology was developed for sensor monitoring and control applications and is thus well suited to sensor communication. The devices are relatively small and low power, and the range is suitable for sensor to tower communication. As with Wi-Fi and Bluetooth, ZigBee's networking protocol adds to the complexity of system integration.

WiMAX and Mobile-Fi may eventually be applicable for tower to central facility communication, which requires transferring potentially large amounts of data over long distance. Both technologies are still early in their development, require large amounts of power, and have yet to establish a firm market.

Table 3-2
Summary of IEEE 802 Technology

Characteristic	Wi-Fi	Bluetooth	ZigBee	WiMAX	Mobile-Fi
Market	Mobile wireless networking	Data exchange between digital devices	Networking of monitoring and control devices	Mobile broadband services for Internet connection; Competes with cellular 3G systems	Mobile broadband services for Internet connection at highways speeds
Range	Low 100's of feet	10's of feet	10 to low 100's of feet	Several km	Several km
Frequency Band	2.4 and 5.8 GHz unlicensed	2.4 GHz unlicensed	800 MHz, 900 MHz, and 2.4 GHZ unlicensed	2 and 6 GHz unlicensed and licensed; no uniform global licensed spectrum	Licensed bands <3.5 GHz
Network Topology	Point-to-point Mesh	Point-to-Point, Point-to-Multipoint	Point-to-Point, Point-to-Multipoint, Mesh	Point-to-point	Unknown
Link Availability	Instantaneous after link established	Instantaneous after link established	Instantaneous after link established	Unknown	Unknown
Link Robustness	Drop outs due to excess number of users or local interference	Good when in range	Multiple frequencies and channels allow adjustments to local interference	Scheduling algorithm	Unknown
Data Throughput	10's of Mbps	100's of kbps	10's to 100's of kbps	10's of Mbps	>1 Mbps
Data Availability	Near instantaneous	Near instantaneous	Near instantaneous	Near instantaneous	Near instantaneous
System Capacity	Many simultaneous users; several 10s of client systems	Master and up to 7 slaves active; up to 255 more inactive	More than 65,000 devices on a single network	High number of users	High number of users
Power Consumption	Several 100 of mW	10's of mW; uW sleep modes	High 10's to 100's of mW; uW sleep modes	Anticipated to be high	Anticipated to be high
Size	Small (on the order of 2 inch^3)	Very small (on the order of 1 inch^3)	Very small (on the order of 1 inch^3)	Unknown	Unknown
Maturity of Technology	Well established; many products	Well established; many products	Well established; many products	New	New
Cost of Communicating Data	Moderately Low	Low	Low	Unknown	Unknown

Non-Standardized Technologies

Non-standardized RF LOS radios are available in off-the-shelf modules and chipsets. These have their own networking and modulation schemes, but general characteristics are summarized in the table below. Custom implementations can be tailored to the application, although modules can be more quickly integrated.

A number of products were scanned to develop the general descriptions of performance characteristics. These products include offerings from Cirronet, Aerocomm, Laipac, MaxStream, Nordic Semiconductor, Holy Stone, FreeWave, and HAC. Point to point and point to multipoint commercial transceiver modules offer a wide range of modules and chipsets that are appropriate for sensor to tower, sensor to mobile platform, and tower to tower communication. Integration of such devices into an instrumented tower system does not typically suffer from the complexities often associated with the network features of an IEEE 802 radio. Communication system capabilities can be tailored by a custom implementation based on a commercially available chipset, but modules based on these chipsets are available and enable rapid, low-risk development with competitive unit cost at lower production volumes.

Table 3-3
Summary of Non-Standardized RF LOS Technology

Characteristic	Description
Range	100's to 1000's of feet, depending on frequency band restrictions
Frequency Band	900 MHz, 2.4 GHz, 5.8 GHz unlicenced
Network Topology	Point-to-point, point-to-multipoint star
Link Availability	Near instantaneous
Link Robustness	Product dependent, but general spread spectrum affords tolerance of certain communication channel impairments
Data Throughput	Low 100's of kbps
Data Availability	Instantaneous
System Capacity	Product dependent
Power Consumption	10's of mW (product and range setting dependent); low power receiver modes; micropower sleep modes
Size	Chipsets: Very small (on the order of sub-inch^3) Modules: Small to medium (on the order of 2–8 inch^3)
Maturity of Technology	Mature; widely available
Cost of Communicating Data	Low

Table 3-4
Summary of IEEE 802 Technology

Characteristic	Wi-Fi	Bluetooth	ZigBee	WiMAX	Mobile-Fi
Market	Mobile wireless networking	Data exchange between digital devices	Networking of monitoring and control devices	Mobile broadband services for Internet connection; Competes with cellular 3G systems	Mobile broadband services for Internet connection at highways speeds
Range	Low 100's of feet	10's of feet	10 to low 100's of feet	Several km	Several km
Frequency Band	2.4 and 5.8 GHz unlicensed	2.4 GHz unlicensed	800 MHz, 900 MHz, and 2.4 GHZ unlicensed	2 and 6 GHz unlicensed and licensed; no uniform global licensed spectrum	Licensed bands <3.5 GHz
Network Topology	Point-to-point Mesh	Point-to-Point, Point-to-Multipoint	Point-to-Point, Point-to-Multipoint, Mesh	Point-to-point	Unknown
Link Availability	Instantaneous after link established	Instantaneous after link established	Instantaneous after link established	Unknown	Unknown
Link Robustness	Drop outs due to excess number of users or local interference	Good when in range	Multiple frequencies and channels allow adjustments to local interference	Scheduling algorithm	Unknown
Data Throughput	10's of Mbps	100's of kbps	10's to 100's of kbps	10's of Mbps	>1 Mbps
Data Availability	Near instantaneous	Near instantaneous	Near instantaneous	Near instantaneous	Near instantaneous
System Capacity	Many simultaneous users; several 10's of client systems	Master and up to 7 slaves active; up to 255 more inactive	More than 65,000 devices on a single network	High number of users	High number of users
Power Consumption	Several 100 of mW	10's of mW; uW sleep modes	High 10's to 100's of mW; uW sleep modes	Anticipated to be high	Anticipated to be high
Size	Small (on the order of 2 inch^3)	Very small (on the order of 1 inch^3)	Very small (on the order of 1 inch^3)	Unknown	Unknown
Maturity of Technology	Well established; many products	Well established; many products	Well established; many productsh	New	New
Cost of Communicating Data	Moderately Low	Low	Low	Unknown	Unknown

3.2.2 RF Wireless Backscatter Technology

RF wireless backscatter technology has been demonstrated for automated overhead transmission line component diagnostics. In contrast with radio transceivers or transponders, RF backscatter devices can be designed with only a few electronic components in order to achieve high reliability and multi-decade maintenance-free service life. RF backscatter devices can be designed to operate passively or with miniscule power consumption, which enables opportunities for environmental power harvesting. The power requirement of radio transceivers or transponders is much greater than RF backscatter devices and therefore significantly limits the potential for battery-less operation and environmental power harvesting.

In an RF backscatter system, an interrogator radio beam is used to stimulate remote sensors and to read the reflected signal energy that is modulated with sensor data. In theory, the sensor could be a purely passive device, such as an RF SAW (surface acoustic wave) resonator. However, a small amount of sensor power is desirable in practice in order to increase the read range, to provide "smarts" to allow operation when several sensors are within range, and to provide flexibility in sensor format.

RF backscatter technology is applicable to short range, low data rate sensor data. This includes sensor to tower, intra-tower, and sensor to mobile communication platforms. Sensors can be automatically interrogated from a reader unit on the tower or a mobile platform passing by the tower/sensor.

Table 3-5
Summary of RF Backscatter Technology

Characteristic	Description
Range	100's of feet
Frequency Band	2.4 GHz unlicensed
Network Topology	Point-to-point
Link Availability	Near instantaneous
Link Robustness	Good with LOS
Data Throughput	Low kbps
Data Availability	Instantaneous
System Capacity	Interrogator and 100's to 1000's of tags
Power Consumption	Interrogator: several watts Tags: microwatts
Size	Interrogator: medium large (on the order of 100s inch^3) Tags: Very small (on the order of 1 inch^3)
Maturity of Technology	Mature
Cost of Communicating Data	Low

3.2.3 RF Wireless Over-the-Horizon Technology

RF wireless OTH technology uses a sky- or space-based repeater to achieve beyond LOS data transfer. A balloon- or aircraft-borne repeater is a common concept and simply uses a repeater for a particular radio technology. This discussion focuses on commercially available space-based repeaters using satellite communication (SATCOM).

There are many commercial SATCOM technologies available for data transfer. Example systems include Iridium, Globalstar, Orbcomm, and Inmarsat services. Iridium is a continuously available global satellite system consisting of 66 low-earth orbiting satellites. Voice and data are communicated using L-band transceivers, and data is available through a ground station. Globalstar is a partially global satellite system consisting of 48 low-earth orbiting satellites. Globalstar uses a bent-pipe architecture for communicating voice and data from a transceiver to ground station, and it utilizes both S- and L-bands. Orbcomm is a global satellite system consisting of 36 low-earth orbiting satellites. Orbcomm uses a store and forward architecture operating in the VHF frequency band and features low cost low power miniature duplex transceivers with data capability. Inmarsat D+ provides near global communication using 10 Inmarsat geostationary orbit satellites. It features low cost messaging implementing low speed, limited length packet messages on L-band channels. Inmarsat Mini-M provides near global communication using geostationary orbit satellites for voice and 6,000 bits/second data within the Inmarsat spot beams. It is intended for fixed asset communication dealing primarily with voice, fax and limited data, and it requires use of a directional antenna.

SATCOM technology is a candidate technology for long-range communication from a tower-based hub to the central facility for low data rate applications. SATCOM does not support video, and most architectures are based on non-continuous, burst transmissions of relatively small data packets. Although some SATCOM technologies advertise low power, these claims are made relative to other SATCOM products and not to low power LOS radios. All SATCOM options charge for air-time, access to services, numbers or messages/bytes/bits, or a flat fee for data transfer. Thus, usage charges for SATCOM services apply over the entire lifetime of the communication system.

Table 3-6
Summary of SATCOM Technology

Characteristic	Description
Range	100's to 1000's of miles; global coverage
Frequency Band	Licensed uplink bands
Network Topology	Point-to-multipoint
Link Availability	System dependent and can be negotiated prior to transmission, collision avoidance, acknowledge-based, or other
Link Robustness	Generally robust, although frequency bands have varying susceptibility to atmospheric effects and systems have different link margins
Data Throughput	Generally kbps
Data Availability	Generally accessible through a ground station interface
System Capacity	1000's of users
Power Consumption	High to very high (watts to 10's of watts)
Size	Medium to large (4 to 100's of inch^3)
Maturity of Technology	Mature
Cost of Communicating Data	High (per use fees, per bit fees, flat fees, and other)

3.2.4 Infrared Technology

Infrared (IR) communication uses electromagnetic radiation with a much higher frequency than radio waves but lower frequency than visible light to communicate data wirelessly. IR communication is commonly applied to remote control of electronic equipment. These devices are typically very low in power consumption and very short range.

Remote control IR technology uses an infrared light-emitting diode (LED) as the transmitter and photodiode as the receiver. The LED emits an infrared signal that is modulated with data, and a lens focuses the modulated signal into a narrow beam. A photodiode at the receiver converts the infrared signal to an electric current.

Although IR technology could support low data rate, short range sensor to sensor and sensor to hub communication, several characteristics of IR technology limit its usefulness for this application. Communication over IR is limited to very short distances, is highly directional in nature, and is susceptible to minor path obstructions due to its strict LOS requirement.

Table 3-7
Summary of Infrared Technology

Characteristic	Description
Range	Up to 10 feet (typical)
Frequency Band	Infrared (800 to 1000 nm typical)
Network Topology	Point-to-point
Link Availability	Instantaneous
Link Robustness	Link is highly directional and susceptible to minor path obstructions
Data Throughput	kbit/s to Mbit/s
Data Availability	Instantaneous
System Capacity	Single user per channel
Power Consumption	Low milliwatts
Size	Very small (on the order of sub-inch^3)
Maturity of Technology	Mature
Cost of Communicating Data	Low

3.2.5 Fiber Optic Technology

Fiber optic technology communicates data by sending light through an optical fiber. Modulated light from an LED or laser is transmitted into a glass or plastic optical fiber. The light reflects off the cladding of the fiber as it travels through the bending fiber. Because there is very little loss due to the reflections, long distances can be traveled. Optical regenerators can be used along the path to regenerate signals so even longer distance can be covered. Optical receivers use a photocell or photodiode to detect the light.

Fiber optic communication is a candidate for the instrumented tower communication infrastructure because it possesses several advantageous characteristics. Its common application is for high bandwidth, long distance data communication, such as wired local-area networks (LAN), so it is well suited to the tower-based hub to central facility link. It is also used in applications where immunity to electromagnetic interference is important or in near high-voltage potentials, because no electricity passes through the fiber. The disadvantage of this technology is the cost and difficulty associated with running the fiber. Also, fiber on the tower could interfere with line maintenance activity and that might lead to reduced reliability (i.e., it would be more susceptible to damage).

Table 3-8
Summary of Fiber Optic Technology

Characteristic	Description
Range	Half mile (to many miles with regenerators)
Frequency Band	Visible to Infrared (650 nm for plastic fibers, 850 to 1300 nm for multi-mode fibers, and 1300 to 1550 nm for single-mode fibers) Wired technology does not require spectral licensing
Network Topology	Point-to-point
Link Availability	Instantaneous
Link Robustness	Robust due to wired point-to-point link
Data Throughput	Mbit/sec to Tbit/sec
Data Availability	Instantaneous
System Capacity	Many simultaneous users
Power Consumption	Several Watts
Size	Medium (10's of inch^3)
Maturity of Technology	Mature
Cost of Communicating Data	Moderately low device costs Cost of deploying a fiber network can be high depending on the area to cover

3.2.6 Free Space Optical Communication Technology

Free space optical communication uses a beam of visible or infrared light to wirelessly communication data line-of-sight. Although similar to fiber optic communication, free space optics transmits signals through space rather than being guided through an optical cable and, unlike wireless RF systems, does not require spectrum licensing. Although relatively unaffected by rain and snow, free space optical communication systems can be severely affected by fog and atmospheric turbulence. Free space optical communication targets high data rate applications such as LAN-to-LAN communication between buildings.

Free space optical technology has a number of disadvantages when compared to other candidates for the instrumented tower communication infrastructure. Although it is high data rate, its range only supports tower to tower (hub to hub) communication. Its high power consumption and large size make it impractical for use on distributed sensor, and its strict LOS requirements make it unsuitable for hub to mobile platform communications.

Table 3-9
Summary of Free Space Optical Technology

Characteristic	Description
Range	Several hundred to several thousand meters
Frequency Band	Infrared (e.g., 830, 1330, 1550 nm)
Network Topology	Point-to-point
Link Availability	Instantaneous
Link Robustness	Robust to electromagnetic interference Susceptible to atmospheric conditions and physical obstructions
Data Throughput	Mbit/sec to Gbit/sec
Data Availability	Instantaneous
System Capacity	Many simultaneous users when multiple point-to-point links established
Power Consumption	Tens of watts
Size	Large (100's of inch^3)
Maturity of Technology	Relatively new
Cost of Communicating Data	Estimated to be moderate

3.2.7 Data Communication Over Power Line

Transmission of data over power lines at first glance seems to fit the instrumented tower concept well in that existing power lines could be used for the infrastructure. However, such systems are not typically tailored for use on transmission lines. Broadband over Power Line (BPL) technology is a fast data communication concept for consumer Internet access. BPL has a number of limitations in the instrumented tower concept. BPL typically launches data waveforms in the 10 to 30 MHz range onto medium-voltage power lines typically used for distribution. BPL avoids high-voltage power lines because the amount of noise on these lines creates too much interference for reliable communication of data. Further, the high inductance of a transformer acts as a low-pass filter and filters the BPL signals. New developments in surface wave propagation promise higher speeds, full duplex communication, and symmetric data rates but do not overcome the previously stated shortfalls of BPL. Other technologies are used for commercial and industrial usage monitoring. For example, Hunt Technologies' power line carrier technologies superimpose data onto power lines at very low data rates and require long integration times at the receiver. Their "ultra-narrow-bandwidth" technology and frequency division multiple access scheme allow for many users and "bi-directional, long-distance communication across a utility's entire infrastructure…without the need or associated costs of repeaters or line conditioning equipment…" (reference: http://www.hunttechnologies.com/pdf/TS2Brochure_.pdf).

One of the challenges of BPL for this application would be coupling the signal onto the energized conductors – this would probably require a high voltage component which would be costly and bring in more risk (i.e., another component to monitor). However on transmission lines that have isolated shield wires this may be an option. It is noted that the utilities have long been using shield wires and phase conductors for communicating information via power line carrier.

3.2.8 Data Communications Summary

Several communication technologies are applicable to the instrumented tower concept. RF wireless LOS and backscatter technologies are applicable to the low data rate sensor or hub to passing platform, as well as low data rate sensor to hub communication due to the short range and relatively low data rates. SATCOM technology has performance that is suitable for hub to OTH relay, but the recurring costs associated with SATCOM are high. Both free space optical technology and certain RF wireless LOS technologies can be used for tower-to-tower communication with the longer distances and the higher data rates needed because of the additive effect of tower-to-tower communication. However, free space optical technology has few advantages over RF wireless LOS in terms of cost, size, and power consumption. Free space optical is better suited for high data rate sensors. Infrared technology is not a good candidate for anything but the shortest range scenarios and very low data rate sensors. Fiber optic communications is well suited to long-haul communication from a hub to the central facility, and fiber optics is a good match for continuous video feeds. Data communication over power lines can be applied to long-haul on but is limited in data rate. As can be seen from the summary tables for each technology, few are able to sustain video data rates. Image snapshots would need to be sent over a period of time, or image processing would need to occur at the camera.

3.3 Mobile Collection Platforms

Mobile platforms could provide an effective and efficient means to deploy sensor and/or communications hub resources in order to cover the wide extents of a power transmission system. Candidate mobile platforms are addressed, organized as follows:

1. Manned
    a. Airplane
    b. Helicopter
    c. Truck
    d. Backpack

2. Unmanned
    a. UAV
    b. Balloon
    c. Satellite
    i. Robotic Crawler

3.3.1 Manned Mobile Platforms

Traditional manned mobile inspection platforms still fit within the instrumented tower system concept. In this case, the man in the loop provides common-sense inspection capabilities (primarily visual, but audible as well) to supplement automatic methods. Fixed and rotary wing aircraft are common for fast fly by inspections. More thorough inspections can be made when time is afforded to drive to each tower and climb. In the future envisioned system, the operator or vehicle will carry a communications hub to collect the local sensor data for eventual relay back to a central location. Sensors may also be carried on the same platform for remote sensing (e.g. cameras). Besides fundamental functional and performance requirements, additional design factors such as size, weight, configuration, battery life, and ergonomics must be considered when designing and packaging sensors and hubs for specific manned mobile platforms. In addition to collecting sensor readings, manned platforms, such as a helicopter, could contain its own sensors and/or collect information for sensors deployed on the transmission line.

3.3.2 Unmanned Mobile Platforms

Unmanned mobile inspection platforms play into a highly automated instrumented tower system concept. In this case, operators are not required for routine data collection and can be deployed with a focus on critical maintenance activity. Data and trend analysis of automatically collected sensor data is expected to provide keen insight into tower locations where human inspection resources should be deployed.

Four unmanned mobile platform types are identified for consideration: UAV, balloon, satellite, and robotic crawler. These platforms all have the same requirement for a generic "black box" payload. By definition, a user interface (display, controls, switches, etc.) is not required for unmanned applications; however test provisions are still likely desired and necessary. In general, the smaller the size, weight, and power consumption of the black box, the more opportunities there will be to integrate it onto mobile platforms. Just like manned sensor platforms, in addition to collecting sensor readings, unmanned platforms, such as a UAV, could contain its own sensors and/or collect information for sensors deployed on the transmission line.

3.3.2.1 Unmanned Aerial Vehicles (UAVs)

Unmanned aerial vehicles (UAVs) have been used primarily for military applications where it is dangerous to send personnel. EPRI has researched the potential for using UAVs for transmission line inspections as is documented in the reference materials cited in the background section of this report. The primary negative with respect to this notion is the liability concern in the event of a catastrophic crash. Also, FAA line-of-sight requirements are restrictive. In the future it is expected that these concerns will be mitigated as related successful ventures are demonstrated and confidence is gained in the technology. Once these barriers are broken, UAVs could become effective mobile inspection platforms carrying sensors and hubs over established transmission line routes.

3.3.2.2 Balloons

Stratospheric balloons or airships can be used for communications relay applications where satellites cannot be afforded. They have strong merit for the instrumented tower application because they provide the benefits of a dedicated satellite at a fraction of the price. Similar to UAV technology, as other industries applications prove this technology, the utility industry will gain the confidence needed to adopt it. The difference between UAVs and balloons is that while UAVs would fly the traditional inspection route, the balloon would be stationed high in the stratosphere serving as a communications relay with coverage of hundreds of miles. The UAV mission would be a matter of hours, while the balloon would be left in the stratosphere as long as possible, possibly months. An advantage of operating in the stratosphere is that the air space is uncontrolled with respect to air traffic control operations. In addition to collecting wireless sensor readings, the ballon could collect and process optical data – visual, IR, UV etc.

The SOUNDER program at SwRI demonstrates the potential for a stratospheric balloon communications relay. The prototype airship has a hemispherical nose and cylindrical middle section with a radius of 3.66 m and overall hull length of 37.8 m. It has a tail structure to provide longitudinal and roll stability. A tail mounted propeller is driven by an electric motor. An array of solar cells is used to collect power. The solar cells, batteries, and power system are centrally located inside the hull, which is transparent. The airship can carry payloads up to 22 lbs. It can "station keep" in the stratosphere for several weeks at an altitude of approximately 70,000 feet. [Reference: Development of a Small Stratospheric Station Keeping Balloon System, International Symposium on Space Technology and Science (ISTS) Proceedings 2000-K-12, Copyright 2000 by Japanese Society for Aeronautical and Space Sciences and ISTS].

The SKYWISP program at SwRI is another example, with much less capability than SOUNDER but with near immediate readiness and low cost. SKYWISP uses a balloon to carry a glider to stratospheric altitudes (80–150 k feet in a few hours), drifts for up to several days, and then drops the glider for a slow spiral descent return over 6–8 hours. The drift segment depends on the jet stream conditions, so the speed and direction cannot be controlled, but this can be monitored from the ground station so the glider can be released for retrieval before moving out of convenient range. The glider can carry small payloads (2 lbs, 16 in^3 non-contiguous) such as a communications hub for the instrumented tower system that could provide radio line-of-sight coverage to towers over hundreds of miles apart. The SKYWISP system is a simple two-man launch-and-forget operation. Gliders, at a cost less than $2k, may be expendable, although the payload may be more valuable. The supporting system required to launch and provide ground control is on the order of $10k non-recurring. Launching and retrieval can be done by 1–2 persons. The cost of this manpower and/or training is not included in the costs cited above.

3.3.2.3 Satellites

There are many space satellites orbiting the earth, both Government and commercial sponsored, for wide ranging applications using advanced sensors and data communications equipment. While it is not reasonable to propose dedicated satellites for the instrumented tower concept, leasing existing satellite services for imagery and data communications is possible now and more options will surely be available in the future.

3.3.2.4 Robotic Crawler Platform

Several have suggested the use of robotic crawlers to traverse transmission lines in order to perform detailed inspections. Several robotic crawlers have been developed. The earliest example found (1991) traveled along the overhead ground cable from tower to tower.[1] A key drawback to this approach is that the robot must remotely sense problems with individual transmission lines. A crawler that attaches directly to the transmission line was recently developed.[2] While both previous approaches are promising, the ability to transfer across a tower was not adequately addressed. The key technical hurdle in traversing transmission lines is crossing the tower connection points. The robot must be capable of crossing a tower without compromising the insulation between the line and tower structure or any

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[1] J. Sawada, K. Kusumoto, Y. Maikawa, T. Munakata, and Y. Ishikawa, \A mobile robot for inspection of power transmission lines," IEEE Transactions on Power Delivery, vol. 6, pp. 309 { 315, Jan. 1991.

[2] S. Peungsungwal, B. Pungsiri, K. Chamnongthai, and M. Okuda, \Autonomous robot for a power transmission line inspection," in Proceedings of the IEEE International Symposium on Circuits and Systems,vol. 3, (Sydney, Australia), pp. 121{124, 6{9 May 2001.

other transmission lines. The method of crossing towers is dependent on the path to the next tower. For example, turns in the transmission lines present design issues that aren't addressed by current robotic crawlers. A successful robotic crawler must be capable of crossing towers in many different configurations. All robotic crawlers presented in the literature are limited to crossing towers on straight sections of transmission lines. Commercial robotic crawler systems do not appear to exist.

A cursory patent search resulted in one applicable patent.[3] The patent covers vehicles that traverse transmission lines and perform inspection tasks. The patent relies on several technologies, such as power harvesting, that have not been fully proven. In addition, the patent does not address the previously identified hurdle of crossing a tower.

The development of a robotic crawler for power line inspection is still in its infancy. In the 15 years since the development of the first robotic crawler noted, very little progress has been made. This is likely due to a lack of funding and the fragmented approaches taken by various power companies. As was mentioned previously, the key technical hurdle of crossing transmission towers in any configuration must be addressed. Other technical areas such as software and electronics issues are important, but will likely benefit from ongoing robotics research. With targeted funding this hurdle could be overcome and a functional prototype developed within 10 years. Once a proof of concept has been developed, the design must be hardened to ensure reliable service. This task could take and additional 5 to 10 years of development.

Summary of Robotic Crawler Platform	
Commercial technology options	None found
Expected improvements over the next 20 years	Prototypes possible within the next 10 years and industrial, hardened, reliable systems possible within 15–20 years.
Physical interface requirements	Ability to cross towers and handle variety of real world configurations.
Power requirements	Estimated 100–500 Watts at 24V (Sensor not included).
Data/bandwidth	Sensor dependent.
Size/weight	10 lbs, weight limited by line carrying limits. Size limited by aerodynamic affects. Minimizing the forces due to wind is critical to ensuring the crawler does not inadvertently touch another transmission line.

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[3] U.S. Patent# 20060114122 – Power Line Inspection Vehicle.

4

Demonstration Scenario

A demonstration of the instrumented tower concept is planned. The fundamental features of the system concept can be demonstrated with a few sensor types installed at one tower (e.g., splice, leakage current, etc.), a fixed communication hub located at the same tower, and a mobile platform (e.g., a utility truck) carrying a communication hub. At least two different communications techniques should be used between sensors and hubs (e.g. backscatter and ZigBee). Having a smart camera in the mix with pan/tilt/zoom features would provide interesting potential for nearly unlimited future expansion of capabilities. At least one of the sensors should be monitored in real time as an alarm for a simulated catastrophic condition, e.g., a system outage. The rest of the sensors can be periodically polled at modest intervals adequate for detection of gradual condition degradation that is typical of power transmission components. Different scenarios can be played out with these key elements to demonstrate a variety of system features and benefits.

A means of automatically communicating sensor data back to a central location should be implemented. With that connectivity in place, the demonstration could be left in place and monitored over the Internet, which may help foster utility participation and maintain interest beyond a short show and tell. Cell phone modems, while not considered to be well suited for a final solution, may prove to be effective for demonstration purposes.

Figure 4-1 below shows a representative block diagram. The hub shown in the diagram would be mounted onto the tower and outfitted with solar panels and rechargeable batteries to run the various communications devices, camera, and tower tilt sensor. In addition to the fixed hub, there would be numerous backscatter and mesh sensors distributed onto tower components for condition monitoring. Not shown is a mobile hub that could alternatively read the individual distributed sensors and/or the aggregate sensor data from the fixed hub.

This section of the report will be later expanded to specify the details of the demonstration system design.

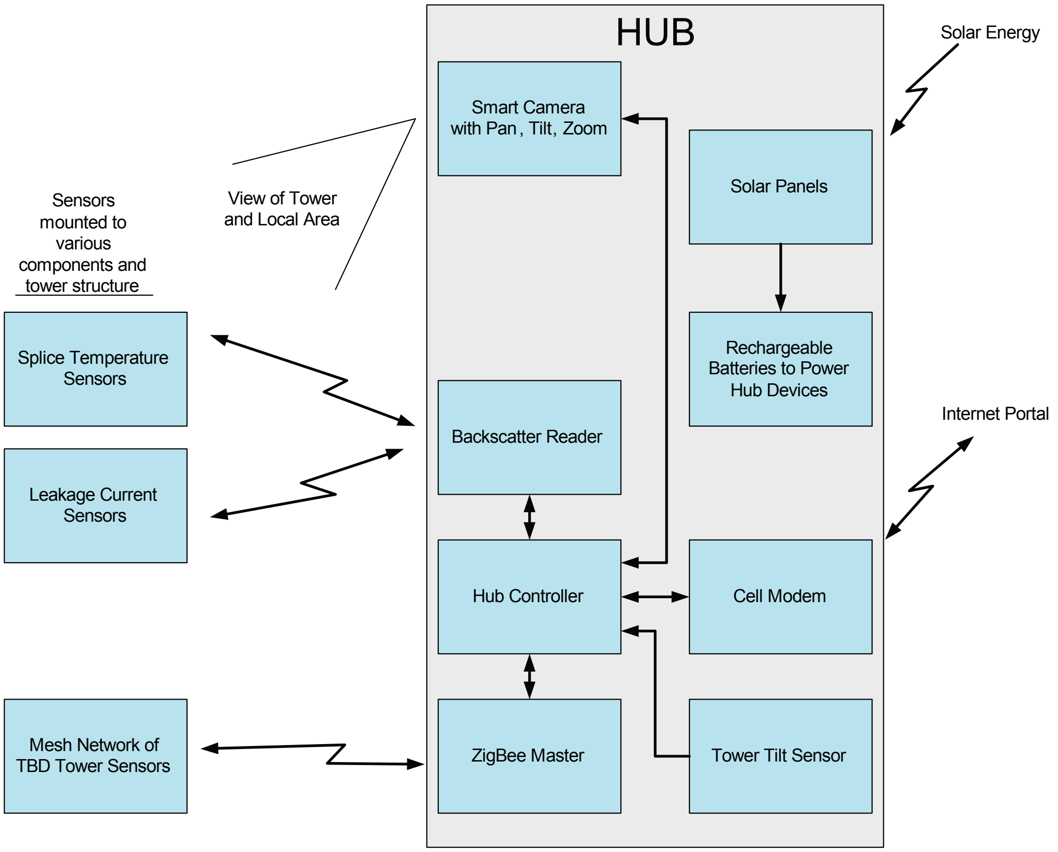

Figure 4-1
Proposed Demonstration System Sensor/Hub Configuration

A SENSING TECHNOLOGY SUMMARY TABLE

Table A-1
Sensing Technology Summary Table

	Commercial Technology Options	Expectations Over the Next 20 Years	Physical Interface Requirements	Power Requirements	Data/Bandwidth	Size/Weight
3.1.1 OPTICAL IMAGE SENSING						
Cameras and Image Processing	Color and monochrome cameras are being applied in many outdoor surveillance applications. Very little software specifically developed for automated transmission line inspection is available but the building blocks for developing such applications exist.	Cameras and image processing computers will become physically smaller with higher resolution and greater processing capability in the future. As computer power increases, image analysis algorithms will become more capable, approaching artificial intelligence goals.	Optical methods are non-contact. Cameras can be equipped with telephoto lenses to increase the stand-off distance though this reduces the field-of-view. Zoom lenses can be used to provide large scene overviews and highly magnified views of critical locations.	Typical voltages are 5 VDC and 12–24 VDC. Power consumption is typically 1 to 5 watts.	Video data rates are required between the camera and image processing computer but data from the camera-computer system will be low bandwidth, digital data describing a specific condition identified by image processing. In addition, it would be desirable to transmit images of the condition for reference or additional interpretation by an operator. Digital images would be in compressed format and might range from 50 to 300 kilobytes.	From 1″ x 1″ x 1″ to 2″ x 2″ x 4″ and weighing from a few ounces to a pound.
Smart Cameras	Sony, VC Vision and others provide monochrome cameras in rugged housings. The Sony system is	The variety and capability of smart cameras will increase rapidly. The systems will become physically smaller with	Optical methods are non-contact. Cameras can be equipped with telephoto lenses to increase the stand-off	Values for the Sony system are: 10.5 to 26.4 volts with 7.5 watts	The camera-computer provides Ethernet, USB 1.1 and RS-232 interfaces as well as digital i/o lines that	The Sony camera can be considered typical for this group. It is 2.3″ x 2.2″ x 4.5″ and weighs 14 ounces

Table A-1
Sensing Technology Summary Table (Continued)

	Commercial Technology Options	Expectations Over the Next 20 Years	Physical Interface Requirements	Power Requirements	Data/Bandwidth	Size/Weight
	based on a 400 MHz x 86 architecture and is compatible with a number of image processing software packages. The VC Vision system is available with either color or monochrome imager and uses a 400 MHz processor from TI	higher resolution and greater processing capability. As computer power increases, more complex image analysis algorithms and software will be included with these systems. Optical methods are non-contact. Cameras can be equipped with t elephoto lenses to increase the stand-off distance though this reduces the field-of-view. Zoom lenses can be used to provide large scene overviews and highly magnified views of critical locations.	distance though this reduces the field-of-view. Zoom lenses can be used to provide large scene overviews and highly magnified views of critical locations.		could be used to control/sample other sensors. Data transmitted from the system will be low bandwidth, digital data describing a specific condition identified by image processing. Digital images would be transmitted in compressed format and might range from 50 to 300 kilobytes.	
3.1.2 INFRARED IMAGE SENSING						
	Systems suitable for outdoor use and transmission line inspection by an operator are available from several manufacturers. Most are battery powered and include image processing functions to	The image resolution of IR cameras will increase as nanotechnology techniques are applied to microbolometer arrays. IR cameras will be produced in greater variety and greater volume due to use in the	As an optical method, thermal IR imaging is non-contact. Stand-off distances can range from several feet to several hundred feet if telephoto lenses are used.	Typically 7–15 VDC 2–15 watts for uncooled cameras	The camera video interface is typically NTSC or PAL. After image analysis, data transmitted from the system will be low bandwidth, digital data describing specific conditions identified by image processing.	Dimensions from 2″ x 2″ x 4″ (excluding lens) to 4″ x 5″ x 9″ Weight from .5 lbs to 4 lbs depending on features and lens

Table A-1
Sensing Technology Summary Table (Continued)

	Commercial Technology Options	Expectations Over the Next 20 Years	Physical Interface Requirements	Power Requirements	Data/Bandwidth	Size/Weight
	enhance and measure temperature differences. IR imagers (without specialized image processing functions) are also available. Additional image analysis would be required for automated identification of thermal hot spots indicating a problem.	surveillance and security areas. The increased volume will result in lower unit prices. "Smart IR cameras", including a programmable image processing computer will be available. Digital interfaces, including USB, Firewire Ethernet and wireless will be included.			Digital images would be transmitted in compressed format and might range from 50 to 300 kilobytes.	
3.1.3 ULTRAVIOLET IMAGE SENSING						
	The DayCor and Coro-Cam 504 cameras are specifically designed and manufactured for transmission line inspection by operators. They could be adapted for use in an automated system. Image resolution ranges from 320 x 240 pixels to roughly 450 TV lines (NTSC format).	Advances in solid state imagers, electronics, and optics will provide smaller and lighter instruments with higher image resolution. It is very likely that stand-alone cameras will be available for integration into automated inspection systems.	Ultraviolet imaging methods are non-contact. UV lenses are limited in availability and most of these cameras use proprietary mounts and lenses.	12 VDC, 10 to 20 watts	Video signals are available through a PAL or NTSC connector. The systems are generally intended for operator use and would require some modification to make use of the image enhancement and photon counting capabilities.	Roughly 6″ x 6″ x 10″ to 15″ long, 6–15 pounds

Table A-1
Sensing Technology Summary Table (Continued)

Commercial Technology Options	Expectations Over the Next 20 Years	Physical Interface Requirements	Power Requirements	Data/Bandwidth	Size/Weight
3.1.4 SATELLITE IMAGE SENSING					
Several companies operate commercial imaging satellites today. Images of selected areas can be purchased for analysis. The current resolution is not sufficient for detecting small conditions but might be used for large objects intruding in the right-of-way or erosion events.	More satellites will be launched, especially as other countries obtain the capability or placing systems in orbit. This should result in lower costs and more timely availability of data. It is less likely that there will be significant improvements in resolution since the most recent system (GeoEye-1) is approaching the limits of atmospheric dispersion.	Satellite imaging is a non-contact, long stand-off inspection method.	NA – provided by satellite	NA	NA
3.1.5 LIDAR					
Current scanning LIDAR systems are complex and expensive. They are used in research programs and by a few service companies providing GIS and topographic data for land use, municipal planning and mineral exploration.	A smaller and simpler LIDAR system with reduced range could be designed if there were a market need. At present there does not appear to be a market that would justify development.	Non-contact	Not known – probably 24 to 120 volts and several hundred watts due to laser power and electronics	Typical image data with a range value at each pixel	Not known

Table A-1
Sensing Technology Summary Table (Continued)

	Commercial Technology Options	Expectations Over the Next 20 Years	Physical Interface Requirements	Power Requirements	Data/Bandwidth	Size/Weight
3.1.6 VIBRATION SENSING						
	Many types of transducers are commercially available with a wide variety of form factors and performance specifications.	Vibration transducers will become smaller and require much less power. The most efficient MEMS accelerometers are already available that require less than a micro-watt of power.	Must be directly coupled to item being measured.	Typically range from 1–500 mW	20–50 kS/sec	Very small and lightweight. Typical dimensions: ½″ cube or less Typical weight: a few grams
3.1.7 ACOUSTIC SENSING						
	Many types of transducers are commercially available with a wide variety of form factors and performance specifications.	Higher sensitivity, smaller form factor, lower power requirements. New designs using MEMS or nano-technology may surface.	No specific mounting requirements.	Typically range from 1–500 mW	50–100 kS/sec	Small and lightweight. Electret and piezoelectric microphones can be a fraction of an inch across, weighing a few grams or less.
3.1.8 STRAIN SENSING						
	Foil or semiconductor strain gauges.	Further development of fiber bragg grating strain gauges for lower cost applications.	Must be physically mounted to structural members at clean, smooth locations.	Typically a few milliwatts	As needed. Continuous monitoring not required.	Very small and lightweight. Foil strain gauges can be a fraction of an inch and weigh a few ounces.

Table A-1
Sensing Technology Summary Table (Continued)

Commercial Technology Options	Expectations Over the Next 20 Years	Physical Interface Requirements	Power Requirements	Data/Bandwidth	Size/Weight
3.1.9 TILT SENSING					
Fluid, electrolytic, pendulum, or solid state	Higher sensitivity, smaller form factor, lower power requirements.	Must be mounted directly to the tower, preferably near the top	20–100 mW, DC input voltage	As needed. Continuous monitoring not required.	Small and lightweight. Typically 1″ cube weighing a few ounces.
3.1.10 MAGNETOSTRICTIVE SENSING (MsS)					
Technology already being used in manned applications in power industry for anchor rods, steel poles, transmission towers, ACSR	The instrumentation will get much smaller, have embedded micro-processors to collect and analyze data, and will incorporate wireless communication technology		Operable from 12 VDC or 110/220 AC, 330 Vpp max at 40 App max for 2 cycles (at 32 KHz for 32 μs up to 250 KHz for 4 μs)	11–54 MBits/sec	11.5″ by 14.5″ by 4″ at 10 lbs …but will be reduced to 5″ by 5″ by 1″ at 2 lbs someday
3.1.11 ULTRASONIC SENSING					
Technology already being used in manned applications in power industry for anchor rods and transmission towers	The instrumentation will get much smaller, have embedded microprocessors to collect and analyze data, and will incorporate wireless communication technology.		Operable from 12 VDC or 110/220 AC, (at 32 KHz for 32 μs up to 250 KHz for 4 μs)	11–54 MBits/sec	Can be as small as 5″ by 5″ by 1″ at 2 lbs but will get even smaller in the future

Table A-1
Sensing Technology Summary Table (Continued)

Commercial Technology Options	Expectations Over the Next 20 Years	Physical Interface Requirements	Power Requirements	Data/Bandwidth	Size/Weight
3.1.12 ELECTROMAGNETIC ACOUSTIC TRANSDUCER (EMAT)					
Technology already being used in manned applications in power industry piping	The instrumentation will get much smaller, have embedded microprocessors to collect and analyze data, and will incorporate wireless communication technology		110/220 AC,	11–54 MBits/sec	Larger than piezoelectric instruments and more expensive
3.1.13 EDDY CURRENT SENSING					
Technology already being used in manned applications in power industry piping	The instrumentation will get much smaller, have embedded microprocessors to collect and analyze data, and will incorporate wireless communication technology		110/220 AC,	11–54 MBits/sec	Larger than piezoelectric instruments and more expensive
3.1.14 GROUND PENETRATING RADAR (GPR)					
3.1.15 PROXIMITY SENSING					
Technology already being used in many commercial applications from garage door openers to counting systems	The instrumentation will get much smaller, have embedded microprocessors to collect and analyze data, and will incorporate wireless communication technology	Flexible, remote sensing options	Battery operable	1 bit of information 1 second update rate may be adequate for tower tampering detection alarm	Relatively small and light

Table A-1
Sensing Technology Summary Table (Continued)

	Commercial Technology Options	Expectations Over the Next 20 Years	Physical Interface Requirements	Power Requirements	Data/Bandwidth	Size/Weight
3.1.16 VOLTAGE POTENTIAL AND HALF CELL MEASUREMENT						
3.1.17 RADIO FREQUENCY INTERFERENCE SENSING						
	Several products available from Radar Engineers, Portland, OR.	Automated detection without need for operator interpretation and associated training.	Remote sensing. Pin-pointing the problem to a particular component is a challenge.	Flexible, battery operated available	Low if processing done at sensor, otherwise can be very high	Flexible, handheld available
3.1.18 LEAKAGE CURRENT SENSING						
	None presently identified, but EPRI development is leading towards commercialization	Power harvesting (solar, etc) could extend life indefinitely beyond practical battery limits	Clamp-around versus in-line configurations; secure mounting to grounded side of component	2.5V at 250 μA	11 byte data payload; read once per hour at most, once per month at least	8.2″ x 6.2″ x 1.6″, approx 4 lbs
3.1.19 DIRECT CONTACT TEMPERATURE SENSING						
	EPRI development is leading towards commercialization; similar commercial up starts are marketed but availability is uncertain	Packaging costs should decrease with time and quantities	Direct contact to splice or conductor	2.5V at 500 μA peak, <50 μA average	5 byte data payload; read once per hour at most, once per month at least	6″ x 2.5″ x 3.5″ sensor, 5″ x 5.5″ x 1″ attachment clamp, Approximately 4 lbs. total
3.1.20 LIGHTNING SENSING AND COUNTING						
	Polyphaser Model LSC-12, LSC-13; May be many others	No insight available	Direct contact to structure; Requires several feet of spacing between sense leads for high sensitivity	9V battery	Few bytes, approx once per month	5″ x 4″ x 2″, Estimate 1–2 lbs. max

Export Control Restrictions

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