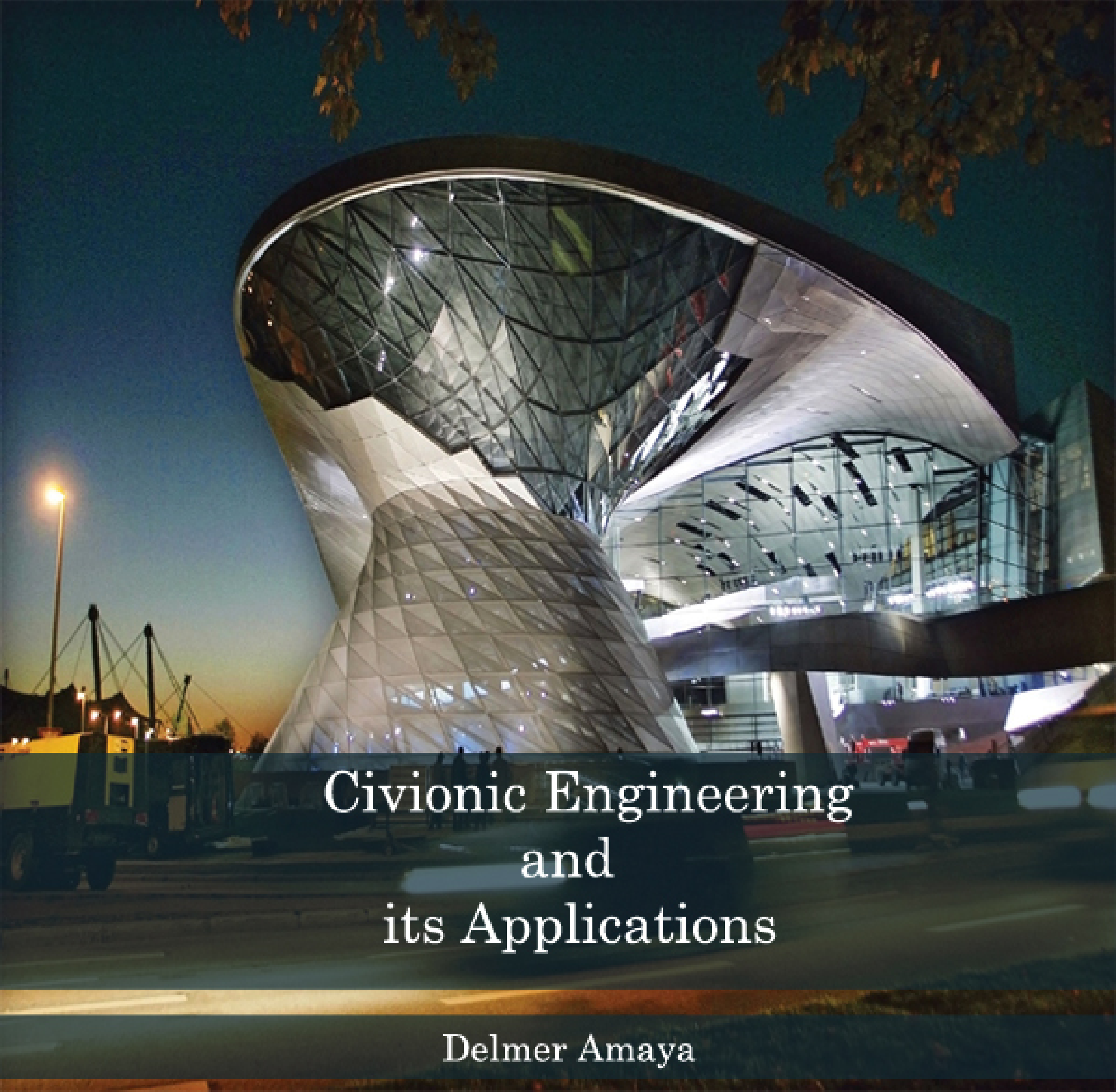

Civionic Engineering and its Applications

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Introduction

Civionics is the combination of electronic engineering with civil engineering, in a manner similar to avionics (**avi**ation and electr**onics**) and mechatronics (**mecha**nical engineering and elec**tronics**). An emerging discipline, the main application area of civionics is currently the use of electronics for structural health monitoring (SHM) of civil structures, particularly photonics (Fiber Optic Bragg Grating).

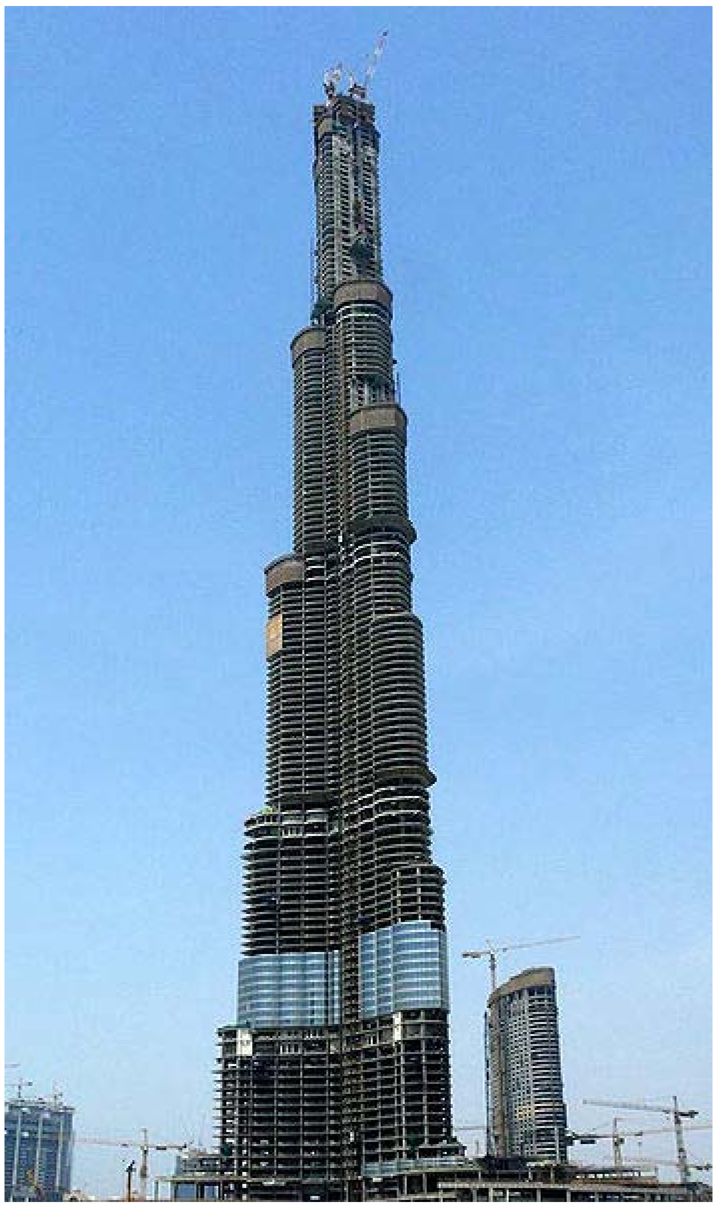
In SHM, Civionics will provide engineers with feedback necessary to aid in optimizing design techniques and understanding infrastructure performance, behaviour and state of condition. The successful integration of intelligent sensing of innovative structures will allow civil structural engineers to expand the design envelope by taking risks to introduce new design concepts, materials and innovation in civil engineering.

Civionic engineering applications include integrating science and technology from both new and traditional disciplines:

- Civil engineering,
- Structural engineering,
- Structural health monitoring,
- Deformation monitoring,
- Automatic Deformation Monitoring System,
- Electronics,
- Metrology,
- Telemetry,
- Remote sensing,
- Wireless sensor network,
- Data acquisition,
- Signal processing,
- Embedded system,
- Fiber Bragg grating,
- Accelerometer,
- Transducer,
- Tensometer

Chapter 1

Structural Engineering



Burj Khalifa, in Dubai, the world's tallest building, shown under construction in 2007 (since completed)

Structural engineering is a field of engineering dealing with the analysis and design of structures that support or resist loads. Structural engineering is usually considered a specialty within civil engineering, but it can also be studied in its own right. Structural engineers are most commonly involved in the design of buildings and large nonbuilding structures but they can also be involved in the design of machinery, medical equipment, vehicles or any item where structural integrity affects the item's function or safety. Structural engineers must ensure their designs satisfy given design criteria, predicated on safety (e.g. structures must not collapse without due warning) or serviceability and performance (e.g. building sway must not cause discomfort to the occupants). Buildings are made to endure massive loads as well as changing climate and natural disasters.

Structural engineering theory is based upon physical laws and empirical knowledge of the structural performance of different landscapes and materials. Structural engineering design utilises a relatively small number of basic structural elements to build up structural systems that can be very complex. Structural engineers are responsible for making creative and efficient use of funds, structural elements and materials to achieve these goals.

Structural engineer

Structural engineers are responsible for engineering design and analysis. Entry-level structural engineers may design the individual structural elements of a structure, for example the beams, columns, and floors of a building. More experienced engineers would be responsible for the structural design and integrity of an entire system, such as a building.

Structural engineers often specialize in particular fields, such as bridge engineering, building engineering, pipeline engineering, industrial structures, or special mechanical structures such as vehicles or aircraft.

Structural engineering has existed since humans first started to construct their own structures. It became a more defined and formalised profession with the emergence of the architecture profession as distinct from the engineering profession during the industrial revolution in the late 19th Century. Until then, the architect and the structural engineer were usually one and the same - the master builder. Only with the development of specialised knowledge of structural theories that emerged during the 19th and early 20th centuries did the professional structural engineer come into existence.

The role of a structural engineer today involves a significant understanding of both static and dynamic loading, and the structures that are available to resist them. The complexity of modern structures often requires a great deal of creativity from the engineer in order to ensure the structures support and resist the loads they are subjected to. A structural engineer will typically have a four or five year undergraduate degree, followed by a minimum of three years of professional practice before being considered fully qualified.

Structural engineers are licensed or accredited by different learned societies and regulatory bodies around the world (for example, the Institution of Structural Engineers in the UK). Depending on the degree course they have studied and/or the jurisdiction they are seeking licensure in, they may be accredited (or licensed) as just structural engineers, or as civil engineers, or as both civil and structural engineers.

History of structural engineering

Pont du Gard, France, a Roman era aqueduct circa 19 BC.

Structural engineering dates back to 2700 BC when the step pyramid for Pharaoh Djoser was built by Imhotep, the first engineer in history known by name. Pyramids were the most common major structures built by ancient civilizations because the structural form of a pyramid is inherently stable and can be almost infinitely scaled (as opposed to most other structural forms, which cannot be linearly increased in size in proportion to increased loads).

Throughout ancient and medieval history most architectural design and construction was carried out by artisans, such as stone masons and carpenters, rising to the role of master builder. No theory of structures existed, and understanding of how structures stood up was extremely limited, and based almost entirely on empirical evidence of 'what had worked before'. Knowledge was retained by guilds and seldom supplanted by advances. Structures were repetitive, and increases in scale were incremental.

No record exists of the first calculations of the strength of structural members or the behaviour of structural material, but the profession of structural engineer only really took shape with the industrial revolution and the re-invention of concrete. The physical sciences underlying structural engineering began to be understood in the Renaissance and have been developing ever since.

Structural failure

The history of structural engineering contains many collapses and failures. Sometimes this is due to obvious negligence, as in the case of the Pétionville school collapse, in which Rev. Fortin Augustin said that *"he constructed the building all by himself, saying he didn't need an engineer as he had good knowledge of construction"* following a partial collapse of the three-story schoolhouse that sent neighbors fleeing. The final collapse killed at least 362 people, mostly children.

In other cases structural failures require careful study, and the results of these inquiries have resulted in improved practices and greater understanding of the science of structural engineering. Some such studies are the result of Forensic engineering investigations where the original engineer seems to have done everything in accordance with the state of the profession and acceptable practice yet a failure still eventuated. A famous case of structural knowledge and practice being advanced in this manner can be found in a series of failures involving Box girders which collapsed in Australia during the 1970s.

Specializations

Building structures

Sydney Opera House, designed by Ove Arup & Partners, with the architect Jørn Utzon

Millennium Dome in London, UK, by Buro Happold and Richard Rogers

Structural building engineering includes all structural engineering related to the design of buildings. It is the branch of structural engineering that is close to architecture.

Structural building engineering is primarily driven by the creative manipulation of materials and forms and the underlying mathematical and scientific ideas to achieve an end which fulfills its functional requirements and is structurally safe when subjected to all the loads it could reasonably be expected to experience. This is subtly different from architectural design, which is driven by the creative manipulation of materials and forms, mass, space, volume, texture and light to achieve an end which is aesthetic, functional and often artistic.

The architect is usually the lead designer on buildings, with a structural engineer employed as a sub-consultant. The degree to which each discipline actually leads the design depends heavily on the type of structure. Many structures are structurally simple and led by architecture, such as multi-storey office buildings and housing, while other structures, such as tensile structures, shells and gridshells are heavily dependent on their form for their strength, and the engineer may have a more significant influence on the form, and hence much of the aesthetic, than the architect.

The structural design for a building must ensure that the building is able to stand up safely, able to function without excessive deflections or movements which may cause fatigue of structural elements, cracking or failure of fixtures, fittings or partitions, or discomfort for occupants. It must account for movements and forces due to temperature, creep, cracking and imposed loads. It must also ensure that the design is practically buildable within acceptable manufacturing tolerances of the materials. It must allow the architecture to work, and the building services to fit within the building and function (air conditioning, ventilation, smoke extract, electrics, lighting etc.). The structural design of a modern building can be extremely complex, and often requires a large team to complete.

Structural engineering specialties for buildings include:

- Earthquake engineering
- Façade engineering
- Fire engineering
- Roof engineering
- Tower engineering
- Wind engineering

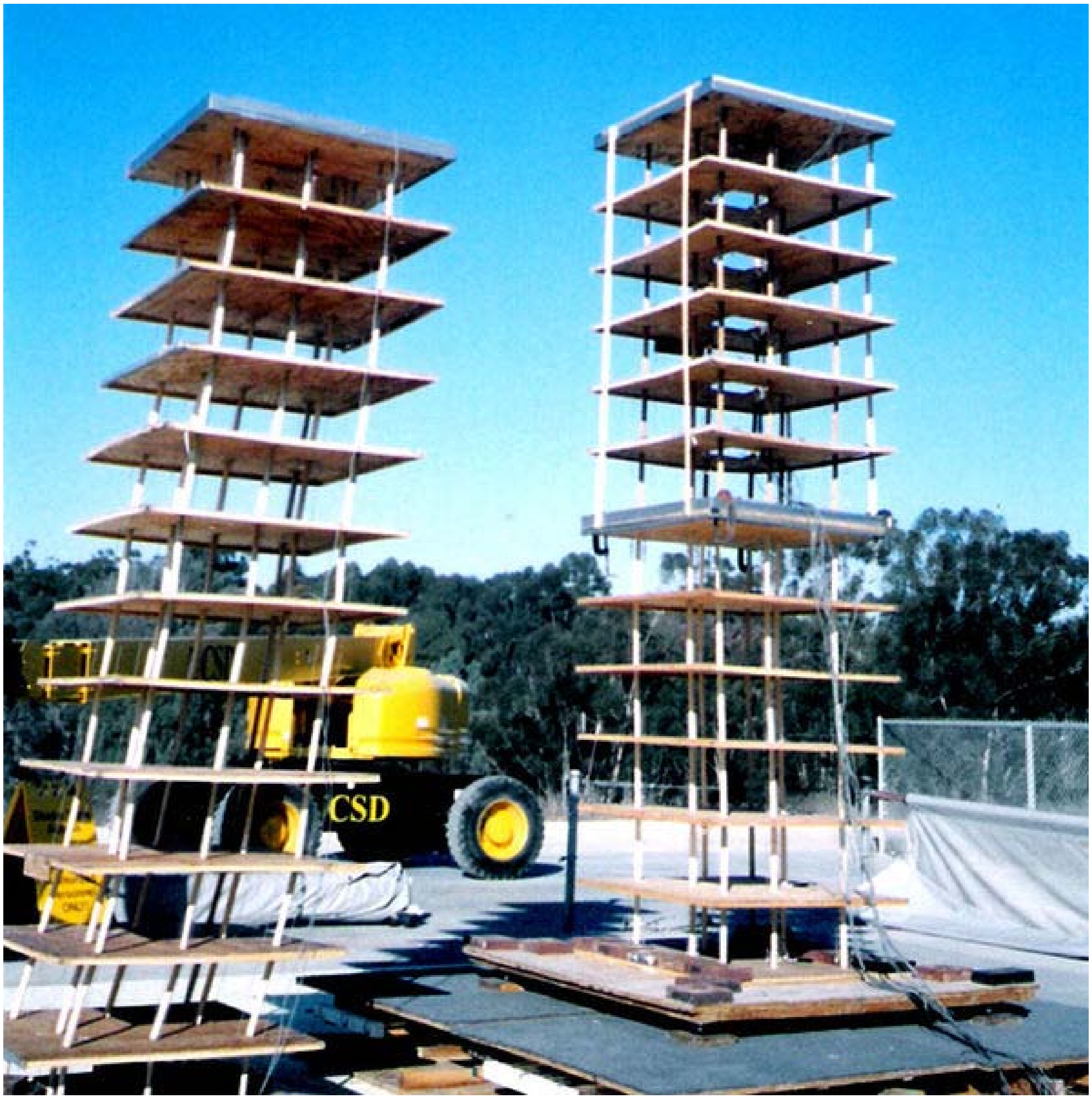
Earthquake engineering structures

Earthquake engineering structures are those engineered to withstand various types of hazardous earthquake exposures at the sites of their particular location.

Earthquake-proof and massive pyramid El Castillo, Chichen Itza

Earthquake engineering is treating its subject structures like defensive fortifications in military engineering but for the warfare on earthquakes. Both earthquake and military general design principles are similar: be ready to slow down or mitigate the advance of a possible attacker.

The main objectives of **earthquake engineering** are:



- Understand interaction of structures with the shaky ground.
- Foresee the consequences of possible earthquakes.
- Design and construct the structures to perform while being exposed to an earthquake.

Earthquake engineering or **earthquake-proof structure** does not, necessarily, means *extremely strong* and *expensive* one like El Castillo pyramid at Chichen Itza shown above. In fact, many structures considered *strong* may in fact be actually *stiff,* which may result in poor seismic performance.

Now, the most *powerful* and *budgetary* tool of the earthquake engineering is base isolation which pertains to the passive structural vibration control technologies.

Civil engineering structures

Civil structural engineering includes all structural engineering related to the built environment. It includes:

- Bridges
- Dams
- Earthworks
- Foundations
- Offshore structures
- Pipelines
- Power stations
- Railways
- Retaining structures and walls
- Roads
- Tunnels
- Waterways
- Water and wastewater infrastructure

The structural engineer is the lead designer on these structures, and often the sole designer. In the design of structures such as these, structural safety is of paramount importance (in the UK, designs for dams, nuclear power stations and bridges must be signed off by a chartered engineer).

Civil engineering structures are often subjected to very extreme forces, such as large variations in temperature, dynamic loads such as waves or traffic, or high pressures from water or compressed gases. They are also often constructed in corrosive environments, such as at sea, in industrial facilities or below ground.

Mechanical structures

An Airbus A380, the world's largest passenger airliner

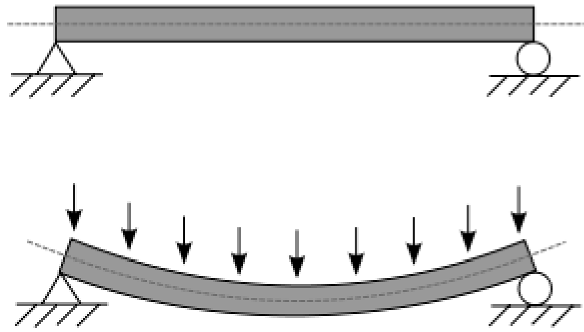
Principals of structural engineering are applied to variety of mechanical (moveable) structures. The design of static structures assumes they always have the same geometry (in fact, so-called static structures can move significantly, and structural engineering design must take this into account where necessary), but the design of moveable or moving structures must account for fatigue, variation in the method in which load is resisted and significant deflections of structures.

The forces which parts of a machine are subjected to can vary significantly, and can do so at a great rate. The forces which a boat or aircraft are subjected to vary enormously and will do so thousands of times over the structure's lifetime. The structural design must ensure that such structures are able to endure such loading for their entire design life without failing.

These works can require mechanical structural engineering:

- Airframes and fuselages
- Boilers and pressure vessels
- Coachworks and carriages
- Cranes
- Elevators
- Escalators
- Marine vessels and hulls

Structural elements



A statically determinate simply supported beam, bending under an evenly distributed load.

Any structure is essentially made up of only a small number of different types of elements:

- Columns
- Beams
- Plates
- Arches
- Shells
- Catenaries

Many of these elements can be classified according to form (straight, plane / curve) and dimensionality (one-dimensional / two-dimensional):

	One-dimensional		**Two-dimensional**	
	straight	**curve**	**plane**	**curve**
(predominantly) bending	beam	continuous arch	plate, concrete slab	lamina, dome
(predominant) tensile stress	rope	Catenary	shell	
(predominant) compression	pier, column		Load-bearing wall	

Columns

Columns are elements that carry only axial force - either tension or compression - or both axial force and bending (which is technically called a beam-column but practically, just a column). The design of a column must check the axial capacity of the element, and the buckling capacity.

The buckling capacity is the capacity of the element to withstand the propensity to buckle. Its capacity depends upon its geometry, material, and the effective length of the column, which depends upon the restraint conditions at the top and bottom of the column. The effective length is $K * l$ where l is the real length of the column.

The capacity of a column to carry axial load depends on the degree of bending it is subjected to, and vice versa. This is represented on an interaction chart and is a complex non-linear relationship.

Beams

A beam may be defined as an element in which one dimemsion is much greater than the other two and the applied loads are usually normal to the main axis of the element. Beams and columns are called line elements and are often represented by simple lines in structural modeling.

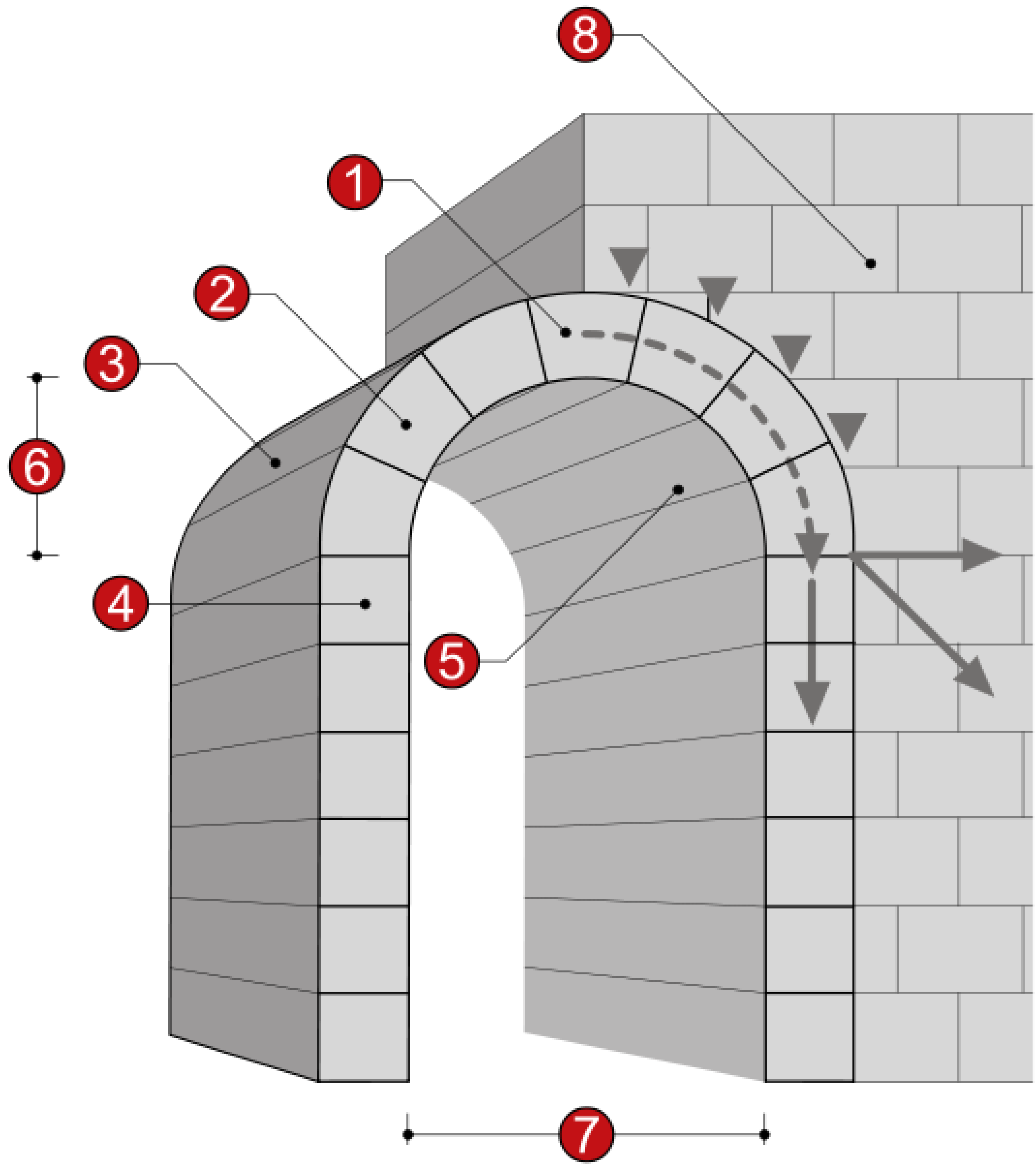
- cantilevered (supported at one end only with a fixed connection)
- simply supported (supported vertically at each end; horizontally on only one to withstand friction, and able to rotate at the supports)
- continuous (supported by three or more supports)
- a combination of the above (ex. supported at one end and in the middle)

Beams are elements which carry pure bending only. Bending causes one part of the section of a beam (divided along its length) to go into compression and the other part into tension. The compression part must be designed to resist buckling and crushing, while the tension part must be able to adequately resist the tension.

Struts and ties

Little Belt: a truss bridge in Denmark

The McDonnell Planetarium by Gyo Obata in St Louis, Missouri, USA, a concrete shell structure



A masonry arch
1. Keystone 2. Voussoir 3. Extrados 4. Impost 5. Intrados 6. Rise 7. Clear span
8. Abutment

A truss is a structure comprising two types of structural elements; compression members and tension members (i.e. struts and ties). Most trusses use gusset plates to connect intersecting elements. Gusset plates are relatively flexible and minimize bending moments at the connections, thus allowing the truss members to carry primarily tension or compression.

Trusses are usually utilised in span large distances, where it would be uneconomical to use solid beams.

Plates

Plates carry bending in two directions. A concrete flat slab is an example of a plate. Plates are understood by using continuum mechanics, but due to the complexity involved they are most often designed using a codified empirical approach, or computer analysis.

They can also be designed with yield line theory, where an assumed collapse mechanism is analysed to give an upper bound on the collapse load. This is rarely used in practice.

Shells

Shells derive their strength from their form, and carry forces in compression in two directions. A dome is an example of a shell. They can be designed by making a hanging-chain model, which will act as a catenary in pure tension, and inverting the form to achieve pure compression.

Arches

Arches carry forces in compression in one direction only, which is why it is appropriate to build arches out of masonry. They are designed by ensuring that the line of thrust of the force remains within the depth of the arch.

Catenaries

Catenaries derive their strength from their form, and carry transverse forces in pure tension by deflecting (just as a tightrope will sag when someone walks on it). They are almost always cable or fabric structures. A fabric structure acts as a catenary in two directions.

Structural engineering theory

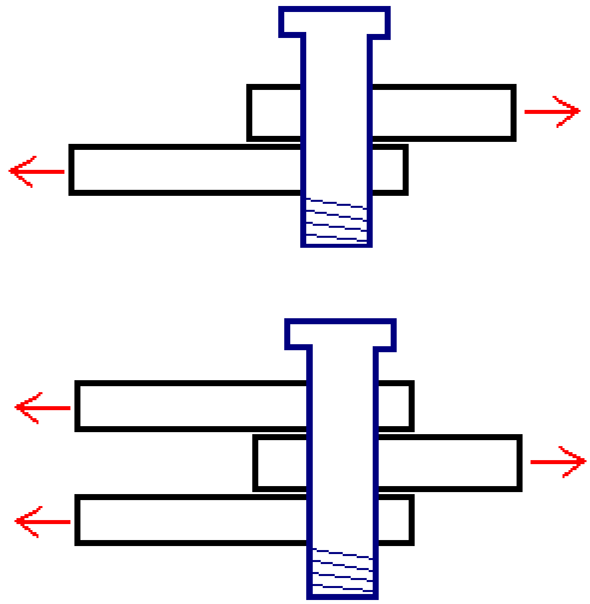


Figure of a bolt in shear stress. Top figure illustrates single shear, bottom figure illustrates double shear.

Structural engineering depends upon a detailed knowledge of loads, physics and materials to understand and predict how structures support and resist self-weight and imposed loads. To apply the knowledge successfully a structural engineer generally requires detailed knowledge of mathematics and relevant empirical and theoretical design codes. As well as, typically, some knowledge of the corrosion resistance of the materials and structures, especially when those structures are exposed to the external environment. Since the 1990s, specialist software has become available to aid in the design of structures, with the functionality to assist in both the drawing and designing of structures with maximum precision; examples include AutoCAD, StaadPro, ETABS etc. Such software may also take into consideration environmental loads, such as from earthquakes and winds.

Materials

The 630 foot (192 m) high, stainless-clad (type 304) Gateway Arch in Saint Louis, Missouri

Structural engineering depends on the knowledge of materials and their properties, in order to understand how different materials support and resist loads.

Common structural materials are:

- Iron:
    - Wrought iron
    - Cast iron
    - Steel
    - Stainless steel
- Concrete:
    - Reinforced concrete
    - Prestressed concrete
- Aluminium
- Composites
- Alloy
- Masonry
- Timber
- Other structural materials:
    - Adobe

- Bamboo
- Carbon fibre
- Fiber reinforced plastic
- Mudbrick
- Roofing materials

Chapter 2

Civil Engineering

The Petronas Twin Towers, designed by architect Cesar Pelli and Thornton-Tomasetti and Ranhill Bersekutu Sdn Bhd engineers, were the world's tallest buildings from 1998 to 2004.

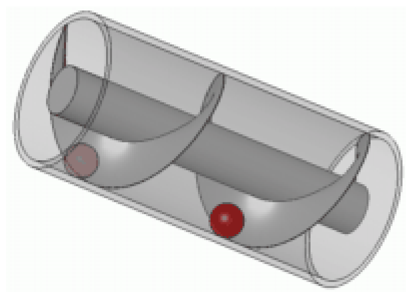
Civil engineering is a professional engineering discipline that deals with the design, construction, and maintenance of the physical and naturally built environment, including works like bridges, roads, canals, dams, and buildings. Civil engineering is the oldest engineering discipline after military engineering, and it was defined to distinguish non-military engineering from military engineering. It is traditionally broken into several sub-disciplines including environmental engineering, geotechnical engineering, structural engineering, transportation engineering, municipal or urban engineering, water resources engineering, materials engineering, coastal engineering, surveying, and construction engineering. Civil engineering takes place on all levels: in the public sector from municipal through to national governments, and in the private sector from individual homeowners through to international companies.

History of the civil engineering profession

The Falkirk Wheel in Scotland.

Engineering has been an aspect of life since the beginnings of human existence. The earliest practices of Civil engineering may have commenced between 4000 and 2000 BC in Ancient Egypt and Mesopotamia (Ancient Iraq) when humans started to abandon a nomadic existence, thus causing a need for the construction of shelter. During this time, transportation became increasingly important leading to the development of the wheel and sailing.

Until modern times there was no clear distinction between civil engineering and architecture, and the term engineer and architect were mainly geographical variations referring to the same person, often used interchangeably. The construction of Pyramids in Egypt (circa 2700-2500 BC) might be considered the first instances of large structure constructions. Other ancient historic civil engineering constructions include the Parthenon by Iktinos in Ancient Greece (447-438 BC), the Appian Way by Roman engineers (c. 312 BC), the Great Wall of China by General Meng T'ien under orders from Ch'in Emperor Shih Huang Ti (c. 220 BC) and the stupas constructed in ancient Sri Lanka like the Jetavanaramaya and the extensive irrigation works in Anuradhapura. The Romans developed civil structures throughout their empire, including especially aqueducts, insulae, harbours, bridges, dams and roads.



The Archimedes screw was operated by hand and could raise water efficiently.

In the 18th century, the term civil engineering was coined to incorporate all things civilian as opposed to military engineering. The first self-proclaimed civil engineer was John Smeaton who constructed the Eddystone Lighthouse. In 1771 Smeaton and some of his colleagues formed the Smeatonian Society of Civil Engineers, a group of leaders of the profession who met informally over dinner. Though there was evidence of some technical meetings, it was little more than a social society.

In 1818 the Institution of Civil Engineers was founded in London, and in 1820 the eminent engineer Thomas Telford became its first president. The institution received a Royal Charter in 1828, formally recognising civil engineering as a profession. Its charter defined civil engineering as:

the art of directing the great sources of power in nature for the use and convenience of man, as the means of production and of traffic in states, both for external and internal trade, as applied in the construction of roads, bridges, aqueducts, canals, river navigation and docks for internal intercourse and exchange, and in the construction of ports, harbours, moles, breakwaters and lighthouses, and in the art of navigation by artificial power for the purposes of commerce, and in the construction and application of machinery, and in the drainage of cities and towns.

The first private college to teach Civil Engineering in the United States was Norwich University founded in 1819 by Captain Alden Partridge. The first degree in Civil Engineering in the United States was awarded by Rensselaer Polytechnic Institute in

1835. The first such degree to be awarded to a woman was granted by Cornell University to Nora Stanton Blatch in 1905.

History of civil engineering

Pont du Gard, France, a Roman aqueduct built circa 19 BC.

Civil engineering is the application of physical and scientific principles, and its history is intricately linked to advances in understanding of physics and mathematics throughout history. Because civil engineering is a wide ranging profession, including several separate specialized sub-disciplines, its history is linked to knowledge of structures, materials science, geography, geology, soils, hydrology, environment, mechanics and other fields.

Throughout ancient and medieval history most architectural design and construction was carried out by artisans, such as stone masons and carpenters, rising to the role of master builder. Knowledge was retained in guilds and seldom supplanted by advances. Structures, roads and infrastructure that existed were repetitive, and increases in scale were incremental.

One of the earliest examples of a scientific approach to physical and mathematical problems applicable to civil engineering is the work of Archimedes in the 3rd century BC, including Archimedes Principle, which underpins our understanding of buoyancy, and practical solutions such as Archimedes' screw. Brahmagupta, an Indian mathematician, used arithmetic in the 7th century AD, based on Hindu-Arabic numerals, for excavation (volume) computations.

The civil engineer

Education and licensure

The Institution of Civil Engineers headquarters in London

Civil engineers typically possess an academic degree with a major in civil engineering. The length of study for such a degree is usually three to five years and the completed degree is usually designated as a Bachelor of Engineering, though some universities designate the degree as a Bachelor of Science. The degree generally includes units covering physics, mathematics, project management, design and specific topics in civil engineering. Initially such topics cover most, if not all, of the sub-disciplines of civil engineering. Students then choose to specialize in one or more sub-disciplines towards the end of the degree. While an Undergraduate (BEng/BSc) Degree will normally provide successful students with industry accredited qualification, some universities offer postgraduate engineering awards (MEng/MSc) which allow students to further specialize in their particular area of interest within engineering.

In most countries, a Bachelor's degree in engineering represents the first step towards professional certification and the degree program itself is certified by a professional body. After completing a certified degree program the engineer must satisfy a range of requirements (including work experience and exam requirements) before being certified. Once certified, the engineer is designated the title of Professional Engineer (in the United States, Canada and South Africa), Chartered Engineer (in most Commonwealth countries), Chartered Professional Engineer (in Australia and New Zealand), or European Engineer (in much of the European Union). There are international engineering agreements between relevant professional bodies which are designed to allow engineers to practice across international borders.

The advantages of certification vary depending upon location. For example, in the United States and Canada "only a licensed engineer may prepare, sign and seal, and submit engineering plans and drawings to a public authority for approval, or seal engineering work for public and private clients.". This requirement is enforced by state and provincial legislation such as Quebec's Engineers Act. In other countries, no such legislation exists. In Australia, state licensing of engineers is limited to the state of Queensland. Practically all certifying bodies maintain a code of ethics that they expect all members to abide by or risk expulsion. In this way, these organizations play an important role in maintaining ethical standards for the profession. Even in jurisdictions where certification has little or no legal bearing on work, engineers are subject to contract law. In cases where an engineer's work fails he or she may be subject to the tort of negligence and, in extreme cases, the charge of criminal negligence. An engineer's work must also comply with numerous other rules and regulations such as building codes and legislation pertaining to environmental law.

Careers

There is no one typical career path for civil engineers. Most people who graduate with civil engineering degrees start with jobs that require a low level of responsibility, and as the new engineers prove their competence, they are trusted with tasks that have larger consequences and require a higher level of responsibility. However, within each branch of civil engineering career path options vary. In some fields and firms, entry-level engineers are put to work primarily monitoring construction in the field, serving as the "eyes and ears" of senior design engineers; while in other areas, entry-level engineers perform the more routine tasks of analysis or design and interpretation. Experienced engineers generally do more complex analysis or design work, or management of more complex design projects, or management of other engineers, or into specialized consulting, including forensic engineering.

Sub-disciplines

In general, civil engineering is concerned with the overall interface of human created fixed projects with the greater world. General civil engineers work closely with surveyors and specialized civil engineers to fit and serve fixed projects within their given site, community and terrain by designing grading, drainage, pavement, water supply, sewer service, electric and communications supply, and land divisions. General engineers spend much of their time visiting project sites, developing community consensus, and preparing construction plans. General civil engineering is also referred to as site engineering, a branch of civil engineering that primarily focuses on converting a tract of land from one usage to another. Civil engineers typically apply the principles of geotechnical engineering, structural engineering, environmental engineering, transportation engineering and construction engineering to residential, commercial, industrial and public works projects of all sizes and levels of construction.

Coastal engineering

Coastal engineering is concerned with managing coastal areas. In some jurisdictions the terms sea defense and coastal protection are used to mean, respectively, defence against flooding and erosion. The term coastal defence is the more traditional term, but coastal management has become more popular as the field has expanded to include techniques that allow erosion to claim land.

Building construction for several apartment blocks

Construction engineering

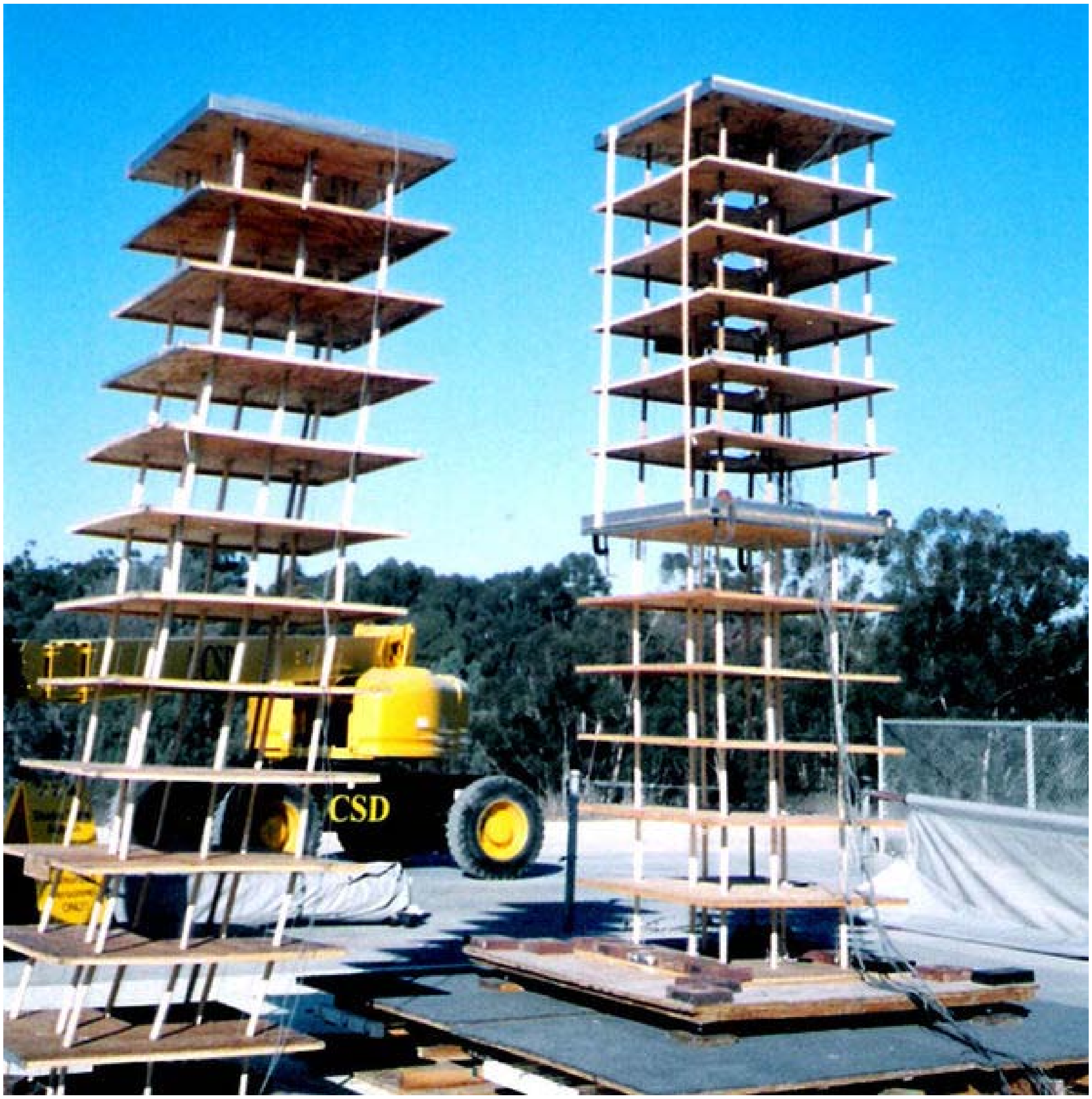
Construction engineering involves planning and execution of the designs from transportation, site development, hydraulic, environmental, structural and geotechnical engineers. As construction firms tend to have higher business risk than other types of civil engineering firms, many construction engineers tend to take on a role that is more business-like in nature: drafting and reviewing contracts, evaluating logistical operations, and closely-monitoring prices of necessary supplies.

Earthquake engineering

Earthquake engineering covers ability of various structures to withstand hazardous earthquake exposures at the sites of their particular location.

Earthquake-proof and massive pyramid El Castillo, Chichen Itza

Earthquake engineering is a sub discipline of the broader category of Structural engineering. The main objectives of earthquake engineering are:



Testing base-isolated (right) and regular (left) building model

- Understand interaction of structures with the shaky ground.
- Foresee the consequences of possible earthquakes.
- Design, construct and maintain structures to perform at earthquake exposure up to the expectations and in compliance with building codes.

Environmental engineering

A filter bed, a part of sewage treatment

Environmental engineering deals with the treatment of chemical, biological, and/or thermal waste, the purification of water and air, and the remediation of contaminated sites, due to prior waste disposal or accidental contamination. Among the topics covered by environmental engineering are pollutant transport, water purification, waste water treatment, air pollution, solid waste treatment and hazardous waste management. Environmental engineers can be involved with pollution reduction, green engineering, and industrial ecology. Environmental engineering also deals with the gathering of information on the environmental consequences of proposed actions and the assessment of effects of proposed actions for the purpose of assisting society and policy makers in the decision making process.

Environmental engineering is the contemporary term for sanitary engineering, though sanitary engineering traditionally had not included much of the hazardous waste management and environmental remediation work covered by the term *environmental engineering*. Some other terms in use are public health engineering and environmental health engineering.

Geotechnical engineering

Construction of an Embankment Dam in Navarra, Spain

Geotechnical engineering is an area of civil engineering concerned with the rock and soil that civil engineering systems are supported by. Knowledge from the fields of geology, material science and testing, mechanics, and hydraulics are applied by geotechnical engineers to safely and economically design foundations, retaining walls, and similar structures. Environmental concerns in relation to groundwater and waste disposal have spawned a new area of study called geoenvironmental engineering where biology and chemistry are important.

Some of the unique difficulties of geotechnical engineering are the result of the variability and properties of soil. Boundary conditions are often well defined in other branches of civil engineering, but with soil, clearly defining these conditions can be impossible. The material properties and behavior of soil are also difficult to predict due to the variability of soil and limited investigation. This contrasts with the relatively well defined material properties of steel and concrete used in other areas of civil engineering. Soil mechanics, which describes the behavior of soil, is also complicated because soils exhibit nonlinear (stress-dependent) strength, stiffness, and dilatancy (volume change associated with application of shear stress).

Water resources engineering

Hoover dam

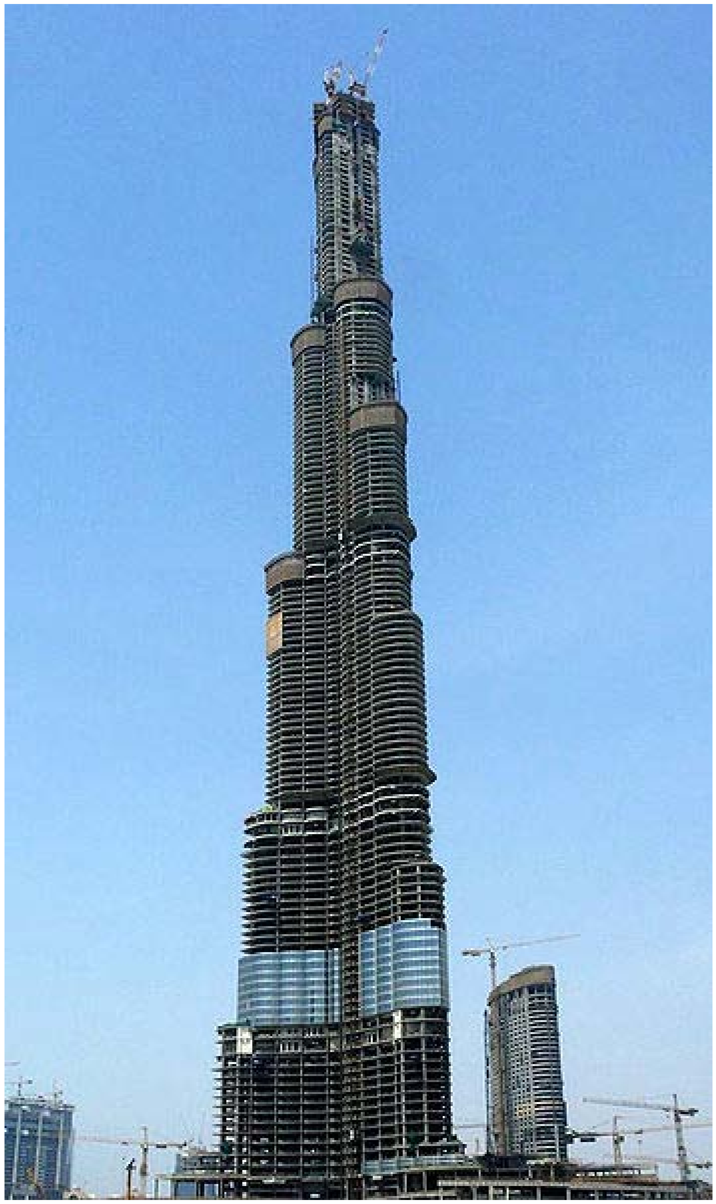
Water resources engineering is concerned with the collection and management of water (as a natural resource). As a discipline it therefore combines hydrology, environmental science, meteorology, geology, conservation, and resource management. This area of civil engineering relates to the prediction and management of both the quality and the quantity of water in both underground (aquifers) and above ground (lakes, rivers, and streams) resources. Water resource engineers analyze and model very small to very large areas of the earth to predict the amount and content of water as it flows into, through, or out of a facility. Although the actual design of the facility may be left to other engineers. Hydraulic engineering is concerned with the flow and conveyance of fluids, principally water. This area of civil engineering is intimately related to the design of pipelines, water supply network, drainage facilities (including bridges, dams, channels, culverts, levees, storm sewers), and canals. Hydraulic engineers design these facilities using the concepts of fluid pressure, fluid statics, fluid dynamics, and hydraulics, among others.

Materials engineering

Another aspect of Civil engineering is materials science. Material engineering deals with ceramics such as concrete, mix asphalt concrete, metals Focus around increased strength, metals such as aluminum and steel, and polymers such as polymethylmethacrylate (PMMA) and carbon fibers.

Materials engineering also consists of protection and prevention like paints and finishes. Alloying is another aspect of material engineering, combining two different types of metals to produce a stronger metal.

Structural engineering



Burj Khalifa, the world's tallest building, in Dubai

Clifton Suspension Bridge, designed by Isambard Kingdom Brunel, in Bristol, UK

Structural engineering is concerned with the structural design and structural analysis of buildings, bridges, towers, flyovers, tunnels, off shore structures like oil and gas fields in the sea, and other structures. This involves identifying the loads which act upon a structure and the forces and stresses which arise within that structure due to those loads, and then designing the structure to successfully support and resist those loads. The loads can be self weight of the structures, other dead load, live loads, moving (wheel) load, wind load, earthquake load, load from temperature change etc. The structural engineer must design structures to be safe for their users and to successfully fulfill the function they are designed for (to be *serviceable*). Due to the nature of some loading conditions, sub-disciplines within structural engineering have emerged, including wind engineering and earthquake engineering.

Design considerations will include strength, stiffness, and stability of the structure when subjected to loads which may be static, such as furniture or self-weight, or dynamic, such as wind, seismic, crowd or vehicle loads, or transitory, such as temporary construction loads or impact. Other considerations include cost, constructability, safety, aesthetics and sustainability.

Surveying

US Navy Surveyor at work with a leveling instrument.

Surveying is the process by which a surveyor measures certain dimensions that generally occur on the surface of the Earth. Surveying equipment, such as levels and theodolites, are used for accurate measurement of angular deviation, horizontal, vertical and slope distances. With computerisation, electronic distance measurement (EDM), total stations, GPS surveying and laser scanning have supplemented (and to a large extent supplanted) the traditional optical instruments. This information is crucial to convert the data into a graphical representation of the Earth's surface, in the form of a map. This information is then used by civil engineers, contractors and even realtors to design from, build on, and trade, respectively. Elements of a building or structure must be correctly sized and positioned in relation to each other and to site boundaries and adjacent structures. Although surveying is a distinct profession with separate qualifications and licensing arrangements, civil engineers are trained in the basics of surveying and mapping, as well as geographic information systems. Surveyors may also lay out the routes of railways, tramway tracks, highways, roads, pipelines and streets as well as position other infrastructures, such as harbors, before construction.

Land Surveying

In the United States, Canada, the United Kingdom and most Commonwealth countries land surveying is considered to be a distinct profession. Land surveyors are not considered to be engineers, and have their own professional associations and licencing requirements. The services of a licenced land surveyor are generally required for boundary surveys (to establish the boundaries of a parcel using its legal description) and subdivision plans (a plot or map based on a survey of a parcel of land, with boundary lines drawn inside the larger parcel to indicated the creation of new boundary lines and roads), both of which are generally referred to as cadastral surveying.

Construction Surveying

Construction surveying is generally performed by specialised technicians. Unlike land surveyors, the resulting plan does not have legal status. Construction surveyors perform the following tasks:

- Survey existing conditions of the future work site, including topography, existing buildings and infrastructure, and even including underground infrastructure whenever possible;
- Construction surveying (otherwise "lay-out" or "setting-out"): to stake out reference points and markers that will guide the construction of new structures such as roads or buildings for subsequent construction;
- Verify the location of structures during construction;
- As-Built surveying: a survey conducted at the end of the construction project to verify that the work authorized was completed to the specifications set on plans.

Transportation engineering

Transportation engineering is concerned with moving people and goods efficiently, safely, and in a manner conducive to a vibrant community. This involves specifying, designing, constructing, and maintaining transportation infrastructure which includes streets, canals, highways, rail systems, airports, ports, and mass transit. It includes areas such as transportation design, transportation planning, traffic engineering, some aspects of urban engineering, queueing theory, pavement engineering, Intelligent Transportation System (ITS), and infrastructure management.

Municipal or urban engineering

Municipal engineering is concerned with municipal infrastructure. This involves specifying, designing, constructing, and maintaining streets, sidewalks, water supply networks, sewers, street lighting, municipal solid waste management and disposal, storage depots for various bulk materials used for maintenance and public works (salt, sand, etc.), public parks and bicycle paths. In the case of underground utility networks, it may also include the civil portion (conduits and access chambers) of the local distribution networks of electrical and telecommunications services. It can also include the optimizing of waste collection and bus service networks. Some of these disciplines overlap with other civil engineering specialties, however municipal engineering focuses on the coordination of these infrastructure networks and services, as they are often built simultaneously, and managed by the same municipal authority.

Chapter 3

Structural Health Monitoring

The process of implementing a damage detection and characterization strategy for engineering structures is referred to as **Structural Health Monitoring** (SHM). Here damage is defined as changes to the material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance. The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. For long term SHM, the output of this process is periodically updated information regarding the ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments. After extreme events, such as earthquakes or blast loading, SHM is used for rapid condition screening and aims to provide, in near real time, reliable information regarding the integrity of the structure.

Origins

Qualitative and non-continuous methods have long been used to evaluate structures for their capacity to serve their intended purpose. Since the beginning of the 19th century, railroad wheel-tappers have used the sound of a hammer striking the train wheel to evaluate if damage was present. In rotating machinery, vibration monitoring has been used for decades as a performance evaluation technique. In the last ten to fifteen years, SHM technologies have emerged creating an exciting new field within various branches of engineering. Academic conferences and scientific journals have been established during this time that specifically focus on SHM. These technologies are currently becoming increasingly common.

Statistical Pattern Recognition Paradigm Approach

The SHM problem can be addressed in the context of a statistical pattern recognition paradigm. This paradigm can be broken down into four parts: (1) Operational Evaluation, (2) Data Acquisition and Cleansing, (3) Feature Extraction and Data Compression, and (4) Statistical Model Development for Feature Discrimination. When one attempts to apply this paradigm to data from real world structures, it quickly becomes apparent that the ability to cleanse, compress, normalize and fuse data to account for operational and environmental variability is a key implementation issue when addressing Parts 2-4 of this paradigm. These processes can be implemented through hardware or software and, in general, some combination of these two approaches will be used.

Operational Evaluation

Operational evaluation attempts to answer four questions regarding the implementation of a damage identification capability:

> i) What are the life-safety and/or economic justification for performing the SHM?
> ii) How is damage defined for the system being investigated and, for multiple damage possibilities, which cases are of the most concern?
> iii) What are the conditions, both operational and environmental, under which the system to be monitored functions?
> iv) What are the limitations on acquiring data in the operational environment?

Operational evaluation begins to set the limitations on what will be monitored and how the monitoring will be accomplished. This evaluation starts to tailor the damage identification process to features that are unique to the system being monitored and tries to take advantage of unique features of the damage that is to be detected.

Data Acquisition, Normalization and Cleansing

The data acquisition portion of the SHM process involves selecting the excitation methods, the sensor types, number and locations, and the data acquisition/storage/transmittal hardware. Again, this process will be application specific. Economic considerations will play a major role in making these decisions. The intervals at which data should be collected is another consideration that must be addressed.

Because data can be measured under varying conditions, the ability to normalize the data becomes very important to the damage identification process. As it applies to SHM, data normalization is the process of separating changes in sensor reading caused by damage from those caused by varying operational and environmental conditions. One of the most common procedures is to normalize the measured responses by the measured inputs. When environmental or operational variability is an issue, the need can arise to normalize the data in some temporal fashion to facilitate the comparison of data measured at similar times of an environmental or operational cycle. Sources of variability in the data acquisition process and with the system being monitored need to be identified and minimized to the extent possible. In general, not all sources of variability can be eliminated. Therefore, it is necessary to make the appropriate measurements such that these sources can be statistically quantified. Variability can arise from changing environmental and test conditions, changes in the data reduction process, and unit-to-unit inconsistencies.

Data cleansing is the process of selectively choosing data to pass on to or reject from the feature selection process. The data cleansing process is usually based on knowledge gained by individuals directly involved with the data acquisition. As an example, an inspection of the test setup may reveal that a sensor was loosely mounted and, hence, based on the judgment of the individuals performing the measurement, this set of data or the data from that particular sensor may be selectively deleted from the feature selection process. Signal processing techniques such as filtering and re-sampling can also be thought of as data cleansing procedures.

Finally, the data acquisition, normalization, and cleansing portion of SHM process should not be static. Insight gained from the feature selection process and the statistical model development process will provide information regarding changes that can improve the data acquisition process.

Feature Extraction and Data Compression

The area of the SHM process that receives the most attention in the technical literature is the identification of data features that allows one to distinguish between the undamaged and damaged structure. Inherent in this feature selection process is the condensation of the data. The best features for damage identification are, again, application specific.

One of the most common feature extraction methods is based on correlating measured system response quantities, such a vibration amplitude or frequency, with the first-hand observations of the degrading system. Another method of developing features for damage identification is to apply engineered flaws, similar to ones expected in actual operating conditions, to systems and develop an initial understanding of the parameters that are sensitive to the expected damage. The flawed system can also be used to validate that the diagnostic measurements are sensitive enough to distinguish between features identified from the undamaged and damaged system. The use of analytical tools such as experimentally-validated finite element models can be a great asset in this process. In many cases the analytical tools are used to perform numerical experiments where the flaws are introduced through computer simulation. Damage accumulation testing, during which significant structural components of the system under study are degraded by subjecting them to realistic loading conditions, can also be used to identify appropriate features. This process may involve induced-damage testing, fatigue testing, corrosion growth, or temperature cycling to accumulate certain types of damage in an accelerated fashion. Insight into the appropriate features can be gained from several types of analytical and experimental studies as described above and is usually the result of information obtained from some combination of these studies.

The operational implementation and diagnostic measurement technologies needed to perform SHM produce more data than traditional uses of structural dynamics information. A condensation of the data is advantageous and necessary when comparisons of many feature sets obtained over the lifetime of the structure are envisioned. Also, because data will be acquired from a structure over an extended period of time and in an operational environment, robust data reduction techniques must be developed to retain feature sensitivity to the structural changes of interest in the presence of environmental and operational variability. To further aid in the extraction and recording of quality data needed to perform SHM, the statistical significance of the features should be characterized and used in the condensation process.

Statistical Model Development

The portion of the SHM process that has received the least attention in the technical literature is the development of statistical models for discrimination between features from the undamaged and damaged structures. Statistical model development is concerned with the implementation of the algorithms that operate on the extracted features to quantify the damage state of the structure. The algorithms used in statistical model development usually fall into three categories. When data are available from both the undamaged and damaged structure, the statistical pattern recognition algorithms fall into the general classification referred to as supervised learning. Group classification and regression analysis are categories of supervised learning algorithms. Unsupervised learning refers to algorithms that are applied to data not containing examples from the damaged structure. Outlier or novelty detection is the primary class of algorithms applied in unsupervised learning applications. All of the algorithms analyze statistical distributions of the measured or derived features to enhance the damage identification process.

The Fundamental Axioms of SHM

Based on the extensive literature that has developed on SHM over the last 20 years, it can be argued that this field has matured to the point where several fundamental axioms, or general principles, have emerged. The axioms are listed as follows:

- Axiom I: All materials have inherent flaws or defects;
- Axiom II: The assessment of damage requires a comparison between two system states;
- Axiom III: Identifying the existence and location of damage can be done in an unsupervised learning mode, but identifying the type of damage present and the damage severity can generally only be done in a supervised learning mode;
- Axiom IVa: Sensors cannot measure damage. Feature extraction through signal processing and statistical classification is necessary to convert sensor data into damage information;
- Axiom IVb: Without intelligent feature extraction, the more sensitive a measurement is to damage, the more sensitive it is to changing operational and environmental conditions;

- Axiom V: The length- and time-scales associated with damage initiation and evolution dictate the required properties of the SHM sensing system;
- Axiom VI: There is a trade-off between the sensitivity to damage of an algorithm and its noise rejection capability;
- Axiom VII: The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation.

SHM Components

SHM System's elements include:

- Structure
- Sensors
- Data acquisition systems
- Data transfer and storage mechanism
- Data management
- Data interpretation and diagnosis:

  1) System Identification
  2) Structural model update
  3) Structural condition assessment
  4) Prediction of remaining service life

An example of this technology is embedding sensors in structures like bridges and aircraft. These sensors provide real time monitoring of various structural changes like stress and strain. In the case of civil engineering structures, the data provided by the sensors is usually transmitted to a remote data acquisition centres. With the aid of modern technology, real time control of structures (Active Structural Control) based on the information of sensors is possible

Examples

Wind and Structural Health Monitoring System for Bridges in Hong Kong

The **Wind and Structural Health Monitoring System** (WASHMS) is a sophisticated bridge monitoring system, costing US$1.3 million, used by the Hong Kong Highways Department to ensure road user comfort and safety of the Tsing Ma, Ting Kau, and Kap Shui Mun bridges that run between Hong Kong and the Hong Kong Airport.

In order to oversee the integrity, durability and reliability of the bridges, WASHMS has four different levels of operation: sensory systems, data acquisition systems, local centralised computer systems and global central computer system.

The sensory system consists of approximately 900 sensors and their relevant interfacing units. With more than 350 sensors on the Tsing Ma bridge, 350 on Ting Kau and 200 on

Kap Shui Mun, the structural behaviour of the bridges is measured 24 hours a day, seven days a week.

The sensors include accelerometers, strain gauges, displacement transducers, level sensing stations, anemometers, temperature sensors and dynamic weight-in-motion sensors. They measure everything from tarmac temperature and strains in structural members to wind speed and the deflection and rotation of the kilometres of cables and any movement of the bridge decks and towers.

These sensors are the early warning system for the bridges, providing the essential information that help the Highways Department to accurately monitor the general health conditions of the bridges.

The structures have been built to withstand up to a one-minute mean wind speed of 95 metres per second. In 1997, when Hong Kong had a direct hit from Typhoon Victor, wind speeds of 110 to 120 kilometres per hour were recorded. However, the highest wind speed on record occurred during Typhoon Wanda in 1962 when a 3 second gust wind speed was recorded at 78.8 metres per second, 284 kilometres per hour.

The information from these hundreds of different sensors is transmitted to the data acquisition outstation units. There are three data acquisition outstation units on Tsing Ma bridge, three on Ting Kau and two on the Kap Shui Mun.

The computing powerhouse for these systems is in the administrative building used by the Highways Department in Tsing Yi. The local central computer system provides data collection control, post-processing, transmission and storage. The global system is used for data acquisition and analysis, assessing the physical conditions and structural functions of the bridges and for integration and manipulation of the data acquisition, analysis and assessing processes.

- Monitoring Hong Kong's Bridges Real-Time Kinematic Spans The Gap

Other large examples

The following project are currently known as some of the biggest on-going bridge monitoring

- The Rio–Antirrio bridge, Greece: has more than 100 sensors monitoring the structure and the traffic in real time.
- Millau Viaduc, France: has one of the largest systems with fiber optics in the world which is considered state of the art.
- The Huey P Long bridge, USA: has over 800 static and dynamic strain gauges designed to measure axial and bending load effects.
- The Fatih Sultan Mehmet Bridge, Turkey: also known as the Second Bosphorus Bridge. It has been monitored using an innovative wireless sensor network with normal traffic condition.

Structural Health Monitoring for bridges

Health monitoring of large bridges shall be performed by simultaneous measurement of loads on the bridge and effects of these loads. It typically includes monitoring of:

- Wind and weather
- Traffic
- Prestressing and stay cables
- Deck
- Pylons
- Ground

Provided with this knowledge, the engineer can:

- Estimate the loads and their effects
- Estimate the state of fatigue
- Forecast the probable evolution of the bridge

References are available that provide an introduction to the application of fiber optic sensors to Structural Health Monitoring on bridges.

Chapter 4

Telemetry

Telemetry is a technology that allows remote measurement and reporting of information. The word is derived from Greek roots *tele* = remote, and *metron* = measure. Systems that need external instructions and data to operate require the counterpart of telemetry, telecommand.

Although the term commonly refers to wireless data transfer mechanisms (e.g. using radio or infrared systems), it also encompasses data transferred over other media, such as a telephone or computer network, optical link or other wired communications. Many modern telemetry systems take advantage of the low cost and ubiquity of GSM networks by using SMS to receive and transmit telemetry data.

History

Telemetering information over wire had its origins in the 19th century. One of the first data transmission circuits was developed in 1845 between the Russian Tsar's Winter Palace and the army's headquarters. In 1874, French engineers built a system of weather and snow-depth sensors on Mont Blanc that transmitted real-time information to Paris. In 1901 the American inventor C. Michalke patented the selsyn, a circuit for sending synchronized rotation information over distances. In 1906, a set of seismic stations were built with telemetering to the Pulkovo Observatory in Russia. In 1912, Commonwealth Edison developed a system of telemetry to monitor electrical loads on its power grid. The Panama Canal (completed 1913-1914) used extensive telemetry systems to monitor locks and water levels.

Wireless telemetry made early appearances in the radiosonde developed concurrently in 1930 by Robert Bureau in France and Pavel Molchanov in Russia. Mochanov's system modulated temperature and pressure measurements by converting them into wireless Morse code. The German V-2 rocket used a system of primitive multiplexed radio signals called "Messina" to report 4 rocket parameters, but it was so unreliable that Von Braun once claimed it was more useful to watch the rocket through binoculars. In both the USA and USSR, the Messina system was quickly replaced with better systems, in both cases based on pulse-position modulation.

Early Soviet missile and space telemetry systems developed in the late 1940s used either pulse-position modulation (e.g., the Tral telemetry system developed by OKB-MEI) or pulse-duration modulation (e.g., the RTS-5 system developed by NII-885). In the USA, early work employed similar systems, but were later replaced by pulse-code modulation (PCM), for example in the Mars probe Mariner 4. Later Soviet interplanetary probes used redundant radio systems, transmitting telemetry by PCM on a decimeter band and PPM on a centimeter band.

Applications

Motor racing

Telemetry is a key factor in modern motor racing, allowing race engineers to interpret the vast amount of data collected during a test or race, and use that to properly tune the car for optimum performance. Systems used in some series, namely Formula One, have become advanced to the point where the potential lap time of the car can be calculated and this is what the driver is expected to meet. Some examples of useful measurements on a race car include accelerations (G forces) in 3 axis, temperature readings, wheel speed, and the displacement of the suspension. In Formula 1, the driver inputs are also recorded so that the team can assess driver performance and, in the case of an accident, the FIA can determine or rule out driver error as a possible cause.

Later developments saw two way telemetry, that allowed the engineers the ability to update calibrations on the car in real time, possibly while it is out on the track. In Formula 1, two-way telemetry surfaced in the early nineties from TAG electronics, and consisted of a message display on the dashboard which the team could update. Its development continued until May 2001, at which point it was first allowed on the cars. By 2002 the teams were able to change engine mapping and deactivate particular engine sensors from the pits while the car was on track. For the 2003 season, the FIA banned two-way telemetry from Formula 1, however the technology still exists and could eventually find its way into other forms of racing or road cars.

In addition to that telemetry has also been applied to the use of Yacht racing. The technology was applied to the Oracle's USA-76.

Agriculture

Most activities related to healthy crops and good yields depend on timely availability of weather and soil data. Therefore, wireless weather stations play a major role in disease prevention and precision irrigation. These stations transmit major parameters needed for good decisions to a base station: air temperature and relative humidity, precipitation and leaf wetness (for disease prediction models), solar radiation and wind speed (to calculate evapotranspiration), water deficit stress (WDS) leaf sensors and soil moisture, crucial to understand the progress of water into soil and roots for irrigation decisions.

Because local micro-climates can vary significantly, such data needs to come from right within the crop. Monitoring stations usually transmit data back by terrestrial radio though occasionally satellite systems are used. Solar power is often employed to make the station independent from local infrastructure.

Water management

Telemetry has become indispensable for water management applications, including water quality and stream gauging functions. Major applications include AMR (automatic meter reading), groundwater monitoring, leak detection in distribution pipelines and equipment surveillance. Having data available in almost real time allows quick reactions to occurrences in the field.

Defense, space and resource exploration systems

Telemetry is an enabling technology for large complex systems such as missiles, RPVs, spacecraft, oil rigs and chemical plants because it allows automatic monitoring, alerting, and record-keeping necessary for safe, efficient operations. Space agencies such as NASA, ESA, and other agencies use telemetry/telecommand systems to collect data from operating spacecraft and satellites.

Telemetry is vital in the development phase of missiles, satellites and aircraft because the system might be destroyed after/during the test. Engineers need critical system parameters to analyze (and improve) the performance of the system. Without telemetry, these data would often be unavailable.

Rocketry

In rocketry, telemetry equipment forms an integral part of the rocket range assets used to monitor the progress of a rocket launch. Some special problems are the extreme environment (temperature, accelerations, vibrations...), the energy supply, the precise alignment of the antenna and (at long distances, e.g. in spaceflight) the signal travel time.

Flight test

Flight test programs typically telemeter data collected from on-board flight test instrumentation over a PCM/RF link. This data is analyzed in real-time for safety reasons and to provide feedback to the test pilot. Particular challenges for telemetering this data includes fading, multipath propagation and the Doppler effect. The bandwidth of the telemetry link is often insufficient to transfer all the data acquired and therefore only a limited set is sent to the ground for real-time processing while an on-board recorder ensures the full dataset is available for post flight analysis.

Enemy intelligence

Telemetry was a vital source of intelligence for the US and UK when Soviet missiles were tested. For this purpose, the US operated a listening post in Iran. Eventually, the Russians discovered this kind of US intelligence gathering and encrypted their telemetry signals of missile tests. Telemetry was a vital source for the Soviets who would operate listening ships in Cardigan Bay to eavesdrop on the UK missile tests carried out there.

Energy monitoring

In factories, buildings, and houses, energy consumption of systems such as HVAC are monitored at multiple locations, together with the related parameters (e.g. temperature) via wireless telemetry to one central location. The information is collected and processed enabling intelligent decisions regarding the most efficient use of energy to be implemented. Such systems also facilitate predictive maintenance.

Resource distribution

Many resources need to be distributed over wide areas. Telemetry is essential in these cases, since it allows the system to channel resources to where they are needed.

Medicine

Telemetry also is used for patients (biotelemetry) who are at risk of abnormal heart activity, generally in a coronary care unit. Such patients are outfitted with measuring, recording and transmitting devices. A data log can be useful in diagnosis of the patient's condition by doctors. An alerting function can alert nurses if the patient is suffering from an acute or dangerous condition.

Also a system that is available in medical-surgical nursing to monitor a condition where heart condition may be ruled out. Or to monitor a response to antiarrhythmic medications such as Digoxin.

Fisheries and wildlife research and management

Common Seal with a transceiver on his back

Telemetry is now being used to study wildlife, and has been particularly useful for monitoring threatened species at the individual level. Animals under study may be fitted with instrumentation ranging from simple tags to cameras, GPS packages and transceivers to provide position and other basic information to scientists and stewards.

Telemetry is used in hydroacoustic assessments for fish which have traditionally employed mobile surveys from boats to evaluate fish biomass and spatial distributions. Conversely, fixed-location techniques use stationary transducers to monitor passing fish. While the first serious attempts to quantify fish biomass were conducted in the 1960s, major advances in equipment and techniques took place at hydropower dams in the 1980s. Some evaluations monitored fish passage 24 hours a day for over a year, producing estimates of fish entrainment rates, fish sizes, and spatial and temporal distributions.

In the 1970s, the dual-beam technique was invented, permitting direct estimation of fish size in-situ via its target strength. The first portable split-beam hydroacoustic system was developed by HTI in 1991, and provided more accurate and less variable estimates of fish target strength than the dual-beam method. It also permitted tracking of fish in 3D, giving each fish's swimming path and absolute direction of movement. This feature proved important for evaluations of entrained fish in water diversions as well as for studies of migratory fish in rivers. In the last 35 years, tens of thousands of mobile and fixed-location hydroacoustic evaluations have been conducted worldwide.

Retail businesses

At a 2005 workshop in Las Vegas, a seminar noted the introduction of telemetry equipment that would allow vending machines to communicate sales and inventory data to a route truck or to a headquarters. This data could be used for a variety of purposes, such as eliminating the need for the driver to make a first trip to see what items need to be restocked before bringing the inventory inside.

Retailers are also beginning to make use of RFID tags to track inventory and prevent shoplifting. Most of these tags passively respond to RFID readers (e.g. at the cashier), but active RFID tags are available that periodically transmit telemetry to a base station.

Law enforcement

Telemetry hardware is useful for tracking persons and property in law enforcement. An ankle collar worn by convicts on probation can warn authorities if a person violates the terms of his or her parole, such as by straying from authorized boundaries or visiting an unauthorized location. Telemetry equipment has also given rise to the concept of bait cars, where law enforcement can rig a car with cameras and tracking equipment and leave it somewhere they expect it to be stolen. When stolen, the telemetry equipment reports the location of the vehicle, and gives law enforcement the ability to deactivate the engine and lock the doors once it is stopped by responding officers.

Electrical energy providers

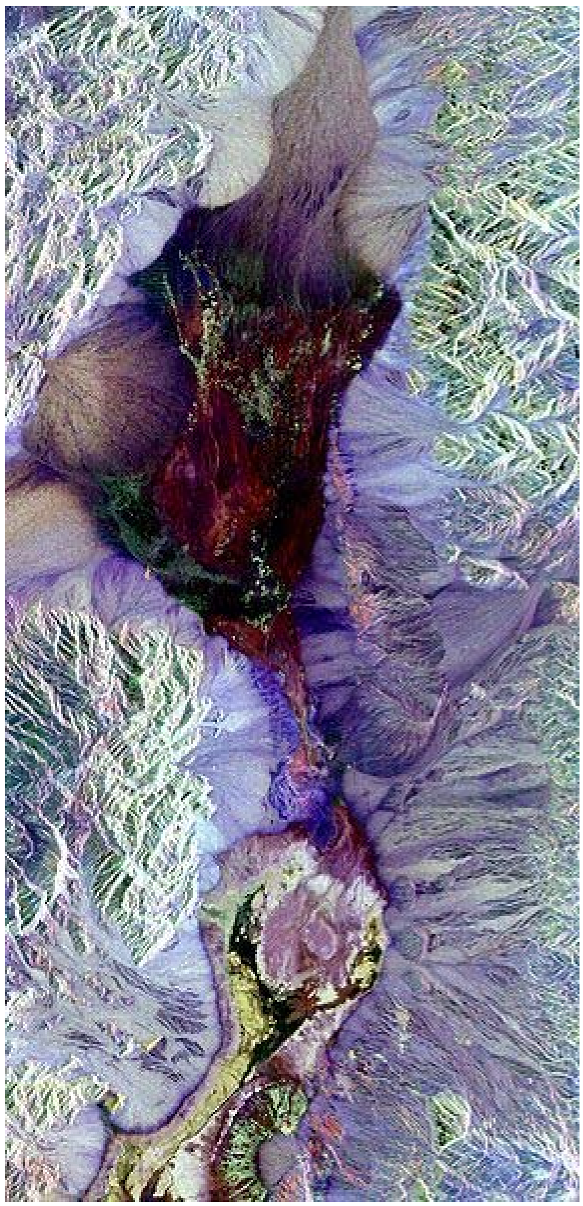
In some countries telemetry is used to assess the amount of electrical energy users have consumed. The electricity meter communicates with a concentrator and the latter sends that information through GPRS or GSM to the electrical energy provider's server.

International standards

As in other telecommunications fields, international standards exist for telemetry equipment and software. CCSDS and IRIG are such standards.

Chapter 5

Remote Sensing



Synthetic aperture radar image of Death Valley colored using polarimetry.

Remote sensing is the small- or large-scale acquisition of information of an object or phenomenon, by the use of either recording or real-time sensing device(s) that are wireless, or not in physical or intimate contact with the object (such as by way of aircraft, spacecraft, satellite, buoy, or ship). In practice, remote sensing is the stand-off collection through the use of a variety of devices for gathering information on a given object or area. Thus, Earth observation or weather satellite collection platforms, ocean and atmospheric observing weather buoy platforms, the monitoring of a parolee via an ultrasound identification system, Magnetic Resonance Imaging (MRI), Positron Emission Tomography (PET), X-radiation (X-RAY) and space probes are all examples of remote sensing. In modern usage, the term generally refers to the use of imaging sensor technologies including: instruments found in aircraft and spacecraft as well as those used in electrophysiology, and is distinct from other imaging-related fields such as medical imaging.

Overview

There are two main types of remote sensing: passive remote sensing and active remote sensing. Passive sensors detect natural radiation that is emitted or reflected by the object or surrounding area being observed. Reflected sunlight is the most common source of radiation measured by passive sensors. Examples of passive remote sensors include film photography, infrared, charge-coupled devices, and radiometers. Active collection, on the other hand, emits energy in order to scan objects and areas whereupon a sensor then detects and measures the radiation that is reflected or backscattered from the target. RADAR is an example of active remote sensing where the time delay between emission and return is measured, establishing the location, height, speed and direction of an object.

Remote sensing makes it possible to collect data on dangerous or inaccessible areas. Remote sensing applications include monitoring deforestation in areas such as the Amazon Basin, glacial features in Arctic and Antarctic regions, and depth sounding of coastal and ocean depths. Military collection during the cold war made use of stand-off collection of data about dangerous border areas. Remote sensing also replaces costly and slow data collection on the ground, ensuring in the process that areas or objects are not disturbed.

Orbital platforms collect and transmit data from different parts of the electromagnetic spectrum, which in conjunction with larger scale aerial or ground-based sensing and analysis, provides researchers with enough information to monitor trends such as El Niño and other natural long and short term phenomena. Other uses include different areas of the earth sciences such as natural resource management, agricultural fields such as land usage and conservation, and national security and overhead, ground-based and stand-off collection on border areas.

By satellite, aircraft, spacecraft, buoy, ship, and helicopter images, data is created to analyze and compare things like vegetation rates, erosion, pollution, forestry, weather, and land use. These things can be mapped, imaged, tracked and observed. The process of remote sensing is also helpful for city planning, archaeological investigations, military observation and geomorphological surveying.

Data acquisition techniques

The basis for multispectral collection and analysis is that of examined areas or objects that reflect or emit radiation that stand out from surrounding areas.

Applications of remote sensing data

- Conventional radar is mostly associated with aerial traffic control, early warning, and certain large scale meteorological data. Doppler radar is used by local law enforcements' monitoring of speed limits and in enhanced meteorological collection such as wind speed and direction within weather systems. Other types of active collection includes plasmas in the ionosphere. Interferometric synthetic aperture radar is used to produce precise digital elevation models of large scale terrain.
- Laser and radar altimeters on satellites have provided a wide range of data. By measuring the bulges of water caused by gravity, they map features on the seafloor to a resolution of a mile or so. By measuring the height and wave-length of ocean waves, the altimeters measure wind speeds and direction, and surface ocean currents and directions.
- Light detection and ranging (LIDAR) is well known in examples of weapon ranging, laser illuminated homing of projectiles. LIDAR is used to detect and measure the concentration of various chemicals in the atmosphere, while airborne LIDAR can be used to measure heights of objects and features on the ground more accurately than with radar technology. Vegetation remote sensing is a principal application of LIDAR.
- Radiometers and photometers are the most common instrument in use, collecting reflected and emitted radiation in a wide range of frequencies. The most common are visible and infrared sensors, followed by microwave, gamma ray and rarely, ultraviolet. They may also be used to detect the emission spectra of various chemicals, providing data on chemical concentrations in the atmosphere.
- Stereographic pairs of aerial photographs have often been used to make topographic maps by imagery and terrain analysts in trafficability and highway departments for potential routes.
- Simultaneous multi-spectral platforms such as Landsat have been in use since the 70's. These thematic mappers take images in multiple wavelengths of electro-magnetic radiation (multi-spectral) and are usually found on Earth observation satellites, including (for example) the Landsat program or the IKONOS satellite. Maps of land cover and land use from thematic mapping can be used to prospect for minerals, detect or monitor land usage, deforestation, and examine the health of indigenous plants and crops, including entire farming regions or forests.
- Within the scope of the combat against desertification, remote sensing allows to follow-up and monitor risk areas in the long term, to determine desertification

factors, to support decision-makers in defining relevant measures of environmental management, and to assess their impacts.

Geodetic

- Overhead geodetic collection was first used in aerial submarine detection and gravitational data used in military maps. This data revealed minute perturbations in the Earth's gravitational field (geodesy) that may be used to determine changes in the mass distribution of the Earth, which in turn may be used for geological studies.

Acoustic and near-acoustic

- Sonar: *passive sonar*, listening for the sound made by another object (a vessel, a whale etc); *active sonar*, emitting pulses of sounds and listening for echoes, used for detecting, ranging and measurements of underwater objects and terrain.
- Seismograms taken at different locations can locate and measure earthquakes (after they occur) by comparing the relative intensity and precise timing.

To coordinate a series of large-scale observations, most sensing systems depend on the following: platform location, what time it is, and the rotation and orientation of the sensor. High-end instruments now often use positional information from satellite navigation systems. The rotation and orientation is often provided within a degree or two with electronic compasses. Compasses can measure not just azimuth (i. e. degrees to magnetic north), but also altitude (degrees above the horizon), since the magnetic field curves into the Earth at different angles at different latitudes. More exact orientations require gyroscopic-aided orientation, periodically realigned by different methods including navigation from stars or known benchmarks.

Resolution impacts collection and is best explained with the following relationship: less resolution=less detail & larger coverage, More resolution=more detail, less coverage. The skilled management of collection results in cost-effective collection and avoid situations such as the use of multiple high resolution data which tends to clog transmission and storage infrastructure.

Data processing

Generally speaking, remote sensing works on the principle of the *inverse problem*. While the object or phenomenon of interest (the **state**) may not be directly measured, there exists some other variable that can be detected and measured (the **observation**), which may be related to the object of interest through the use of a data-derived computer model. The common analogy given to describe this is trying to determine the type of animal from its footprints. For example, while it is impossible to directly measure temperatures in the upper atmosphere, it is possible to measure the spectral emissions from a known chemical species (such as carbon dioxide) in that region. The frequency of the emission may then be related to the temperature in that region via various thermodynamic relations.

The quality of remote sensing data consists of its spatial, spectral, radiometric and temporal resolutions.

Spatial resolution
: The size of a pixel that is recorded in a raster image – typically pixels may correspond to square areas ranging in side length from 1 to 1,000 metres (3.3 to 3,300 ft).

Spectral resolution
: The wavelength width of the different frequency bands recorded – usually, this is related to the number of frequency bands recorded by the platform. Current Landsat collection is that of seven bands, including several in the infra-red spectrum, ranging from a spectral resolution of 0.07 to 2.1 μm. The Hyperion sensor on Earth Observing-1 resolves 220 bands from 0.4 to 2.5 μm, with a spectral resolution of 0.10 to 0.11 μm per band.

Radiometric resolution
: The number of different intensities of radiation the sensor is able to distinguish. Typically, this ranges from 8 to 14 bits, corresponding to 256 levels of the gray scale and up to 16,384 intensities or "shades" of colour, in each band. It also depends on the instrument noise.

Temporal resolution
: The frequency of flyovers by the satellite or plane, and is only relevant in time-series studies or those requiring an averaged or mosaic image as in deforesting monitoring. This was first used by the intelligence community where repeated coverage revealed changes in infrastructure, the deployment of units or the modification/introduction of equipment. Cloud cover over a given area or object makes it necessary to repeat the collection of said location.

In order to create sensor-based maps, most remote sensing systems expect to extrapolate sensor data in relation to a reference point including distances between known points on the ground. This depends on the type of sensor used. For example, in conventional photographs, distances are accurate in the center of the image, with the distortion of measurements increasing the farther you get from the center. Another factor is that of the platen against which the film is pressed can cause severe errors when photographs are used to measure ground distances. The step in which this problem is resolved is called georeferencing, and involves computer-aided matching up of points in the image (typically 30 or more points per image) which is extrapolated with the use of an established benchmark, "warping" the image to produce accurate spatial data. As of the early 1990s, most satellite images are sold fully georeferenced.

In addition, images may need to be radiometrically and atmospherically corrected.

Radiometric correction

gives a scale to the pixel values, e. g. the monochromatic scale of 0 to 255 will be converted to actual radiance values.

Atmospheric correction

eliminates atmospheric haze by rescaling each frequency band so that its minimum value (usually realised in water bodies) corresponds to a pixel value of 0. The digitizing of data also make possible to manipulate the data by changing gray-scale values.

Interpretation is the critical process of making sense of the data. The first application was that of aerial photographic collection which used the following process; spatial measurement through the use of a light table in both conventional single or stereographic coverage, added skills such as the use of photogrammetry, the use of photomosaics, repeat coverage, Making use of objects' known dimensions in order to detect modifications. Image Analysis is the recently developed automated computer-aided application which is in increasing use.

Object-Based Image Analysis (OBIA) is a sub-discipline of GIScience devoted to partitioning remote sensing (RS) imagery into meaningful image-objects, and assessing their characteristics through spatial, spectral and temporal scale.

Old data from remote sensing is often valuable because it may provide the only long-term data for a large extent of geography. At the same time, the data is often complex to interpret, and bulky to store. Modern systems tend to store the data digitally, often with lossless compression. The difficulty with this approach is that the data is fragile, the format may be archaic, and the data may be easy to falsify. One of the best systems for archiving data series is as computer-generated machine-readable ultrafiche, usually in typefonts such as OCR-B, or as digitized half-tone images. Ultrafiches survive well in standard libraries, with lifetimes of several centuries. They can be created, copied, filed and retrieved by automated systems. They are about as compact as archival magnetic media, and yet can be read by human beings with minimal, standardized equipment.

Data processing levels

To facilitate the discussion of data processing in practice, several processing "levels" were first defined in 1986 by NASA as part of its Earth Observing System and steadily adopted since then, both internally at NASA (e. g.,) and elsewhere (e. g.,); these definitions are:

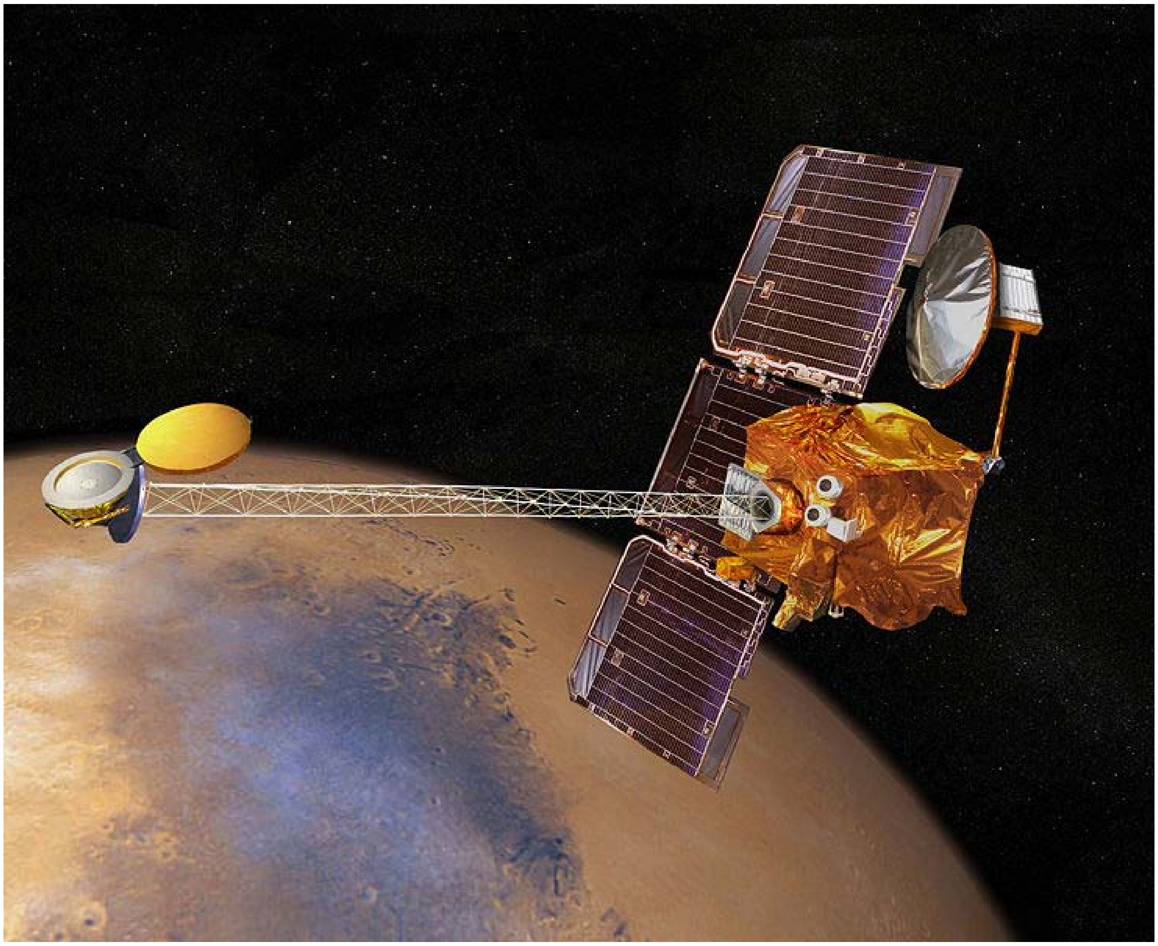
Level	Description
0	Reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artifacts (e. g., synchronization frames, communications headers, duplicate data) removed.
1a	Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (e. g., platform ephemeris)

	computed and appended but not applied to the Level 0 data (or if applied, in a manner that level 0 is fully recoverable from level 1a data).
1b	Level 1a data that have been processed to sensor units (e. g., radar backscatter cross section, brightness temperature, etc.); not all instruments have Level 1b data; level 0 data is not recoverable from level 1b data.
2	Derived geophysical variables (e. g., ocean wave height, soil moisture, ice concentration) at the same resolution and location as Level 1 source data.
3	Variables mapped on uniform spacetime grid scales, usually with some completeness and consistency (e. g., missing points interpolated, complete regions mosaicked together from multiple orbits, etc).
4	Model output or results from analyses of lower level data (i. e., variables that were not measured by the instruments but instead are derived from these measurements).

A Level 1 data record is the most fundamental (i. e., highest reversible level) data record that has significant scientific utility, and is the foundation upon which all subsequent data sets are produced. Level 2 is the first level that is directly usable for most scientific applications; its value is much greater than the lower levels. Level 2 data sets tend to be less voluminous than Level 1 data because they have been reduced temporally, spatially, or spectrally. Level 3 data sets are generally smaller than lower level data sets and thus can be dealt with without incurring a great deal of data handling overhead. These data tend to be generally more useful for many applications. The regular spatial and temporal organization of Level 3 datasets makes it feasible to readily combine data from different sources.

History

The TR-1 reconnaissance/surveillance aircraft.



The *2001 Mars Odyssey* used spectrometers and imagers to hunt for evidence of past or present water and volcanic activity on Mars.

Beyond the primitive methods of remote sensing our earliest ancestors used (ex.: standing on a high cliff or tree to view the landscape), the modern discipline arose with the development of flight. The balloonist G. Tournachon (alias Nadar) made photographs of Paris from his balloon in 1858. Messenger pigeons, kites, rockets and unmanned balloons were also used for early images. With the exception of balloons, these first, individual images were not particularly useful for map making or for scientific purposes.

Systematic aerial photography was developed for military surveillance and reconnaissance purposes beginning in World War I and reaching a climax during the Cold War with the use of modified combat aircraft such as the P-51, P-38, RB-66 and the F-4C, or specifically designed collection platforms such as the U2/TR-1, SR-71, A-5 and the OV-1 series both in overhead and stand-off collection. A more recent development is that of increasingly smaller sensor pods such as those used by law enforcement and the military, in both manned and unmanned platforms. The advantage of this approach is that this requires minimal modification to a given airframe. Later imaging technologies would include Infra-red, conventional, doppler and synthetic aperture radar.

The development of artificial satellites in the latter half of the 20th century allowed remote sensing to progress to a global scale as of the end of the Cold War. Instrumentation aboard various Earth observing and weather satellites such as Landsat, the Nimbus and more recent missions such as RADARSAT and UARS provided global measurements of various data for civil, research, and military purposes. Space probes to other planets have also provided the opportunity to conduct remote sensing studies in extraterrestrial environments, synthetic aperture radar aboard the Magellan spacecraft provided detailed topographic maps of Venus, while instruments aboard SOHO allowed studies to be performed on the Sun and the solar wind, just to name a few examples.

Recent developments include, beginning in the 1960s and 1970s with the development of image processing of satellite imagery. Several research groups in Silicon Valley including NASA Ames Research Center, GTE and ESL Inc. developed Fourier transform techniques leading to the first notable enhancement of imagery data.

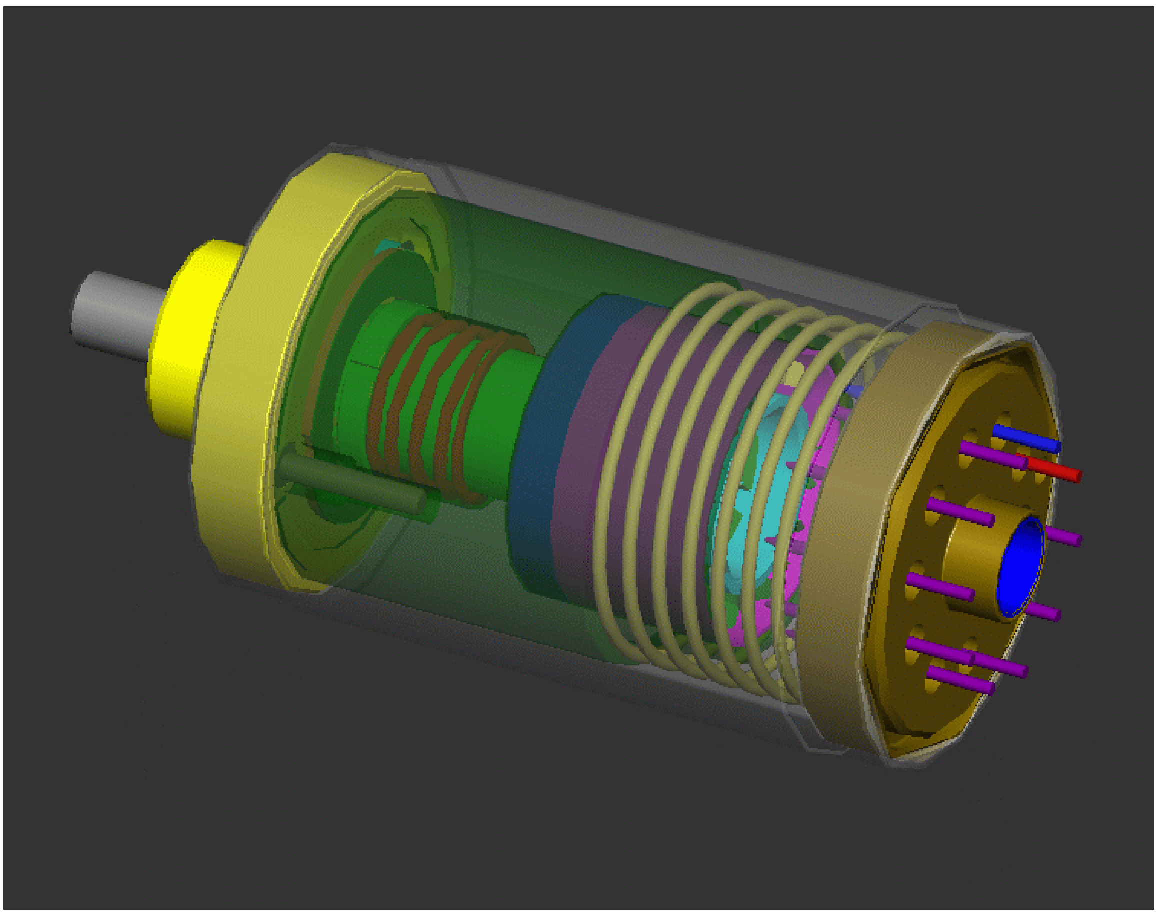
The introduction of online web services for easy access to remote sensing data in the 21st century (mainly low/medium-resolution images), like Google Earth, has made remote sensing more familiar to the big public and has popularized the science.

Remote Sensing software

Remote Sensing data is processed and analyzed with computer software, known as a remote sensing application. A large number of proprietary and open source applications exist to process remote sensing data. According to an NOAA Sponsored Research by Global Marketing Insights, Inc. the most used applications among Asian academic groups involved in remote sensing are as follows: ERDAS 36% (ERDAS IMAGINE 25% & ERMapper 11%); ESRI 30%; ITT Visual Information Solutions ENVI 17%; MapInfo 17%. Among Western Academic respondents as follows: ESRI 39%, ERDAS IMAGINE 27%, MapInfo 9%, AutoDesk 7%, ITT Visual Information Solutions ENVI 17%. Other important Remote Sensing Software packages include: TNTmips from MicroImages, PCI Geomatica made by PCI Geomatics, the leading remote sensing software package in Canada, IDRISI from Clark Labs, Image Analyst from Intergraph, RemoteView made by Overwatch Textron Systems, and the original object based image analysis software eCognition from Definiens. Dragon/ips is one of the oldest remote sensing packages still available, and is in some cases free. Open source remote sensing software includes GRASS GIS, QGIS, OSSIM, Opticks (software) and Orfeo toolbox.

Chapter 6

Accelerometer



A depiction of an accelerometer designed at Sandia National Laboratories.

An **accelerometer** is a device that measures the proper acceleration of the device. This is *not necessarily* the same as the coordinate acceleration (change of velocity of the device in space), but is rather the type of acceleration associated with the phenomenon of weight experienced by a test mass that resides in the frame of reference of the accelerometer device. For an example of where these types of acceleration differ, an accelerometer will measure a value when sitting on the ground, because masses there have weights, even though they do not change velocity. However, an accelerometer in gravitational free fall toward the center of the Earth will measure a value of zero because, even though its speed is increasing, it is in an inertial frame of reference, in which it is weightless.

An accelerometer thus measures **weight per unit of (test) mass**, a quantity also known as specific force, or g-force. Another way of stating this is that by measuring weight, an accelerometer measures the acceleration of the free-fall reference frame (inertial reference frame) relative to itself.

Most accelerometers do not display the value they measure, but supply it to other devices. Real accelerometers also have practical limitations in how quickly they respond to changes in acceleration, and cannot respond to changes above a certain frequency of change.

Single- and multi-axis models of accelerometer are available to detect magnitude and direction of the proper acceleration (or g-force), as a vector quantity, and can be used to sense orientation (because direction of weight changes), coordinate acceleration (so long as it produces g-force or a change in g-force), vibration, shock, and falling (a case where the proper acceleration changes, since it tends toward zero). Micromachined accelerometers are increasingly present in portable electronic devices and video game controllers, to detect the position of the device or provide for game input.

Pairs of accelerometers extended over a region of space can be used to detect differences (gradients) in the proper accelerations of frames of references associated with those points. These devices are called gradiometers, as they measure gradients in the gravitational field. Such pairs of accelerometers in theory may also be able to detect gravity waves.

Physical principles

An accelerometer measures proper acceleration, which is the acceleration it experiences relative to freefall and is the acceleration felt by people and objects. Put another way, at any point in spacetime the equivalence principle guarantees the existence of a local inertial frame, and an accelerometer measures the acceleration relative to that frame. Such accelerations are popularly measured in terms of g-force.

An accelerometer at rest relative to the Earth's surface will indicate approximately 1 g *upwards*, because any point on the Earth's surface is accelerating upwards relative to the local inertial frame (the frame of a freely falling object near the surface). To obtain the acceleration due to motion with respect to the Earth, this "gravity offset" must be subtracted and corrections for effects caused by the Earth's rotation relative to the inertial frame.

The reason for the appearance of a gravitational offset is Einstein's equivalence principle, which states that the effects of gravity on an object are indistinguishable from acceleration. When held fixed in a gravitational field by, for example, applying a ground reaction force or an equivalent upward thrust, the reference frame for an accelerometer (its own casing) accelerates upwards with respect to a free-falling reference frame. The effects of this acceleration are indistinguishable from any other acceleration experienced by the instrument, so that an accelerometer cannot detect the difference between sitting in a rocket on the launch pad, and being in the same rocket in deep space while it uses its engines to accelerate at 1 g. For similar reasons, an accelerometer will read *zero* during any type of free fall. This includes use in a coasting spaceship in deep space far from any mass, a spaceship orbiting the Earth, an airplane in a parabolic "zero-g" arc, or any free-fall in vacuum. Another example is free-fall at a sufficiently high altitude that atmospheric effects can be neglected.

However this does not include a (non-free) fall in which air resistance produces drag forces that reduce the acceleration, until constant terminal velocity is reached. At terminal velocity the accelerometer will indicate 1 g acceleration upwards. For the same reason a skydiver, upon reaching terminal velocity, does not feel as though he or she were in "free-fall", but rather experiences a feeling similar to being supported (at 1 g) on a "bed" of uprushing air.

Acceleration is quantified in the SI unit metres per second per second (m/s^2), in the cgs unit gal (Gal), or popularly in terms of g-force (*g*).

For the practical purpose of finding the acceleration of objects with respect to the Earth, such as for use in an inertial navigation system, a knowledge of local gravity is required. This can be obtained either by calibrating the device at rest, or from a known model of gravity at the approximate current position.

Structure

Conceptually, an accelerometer behaves as a damped mass on a spring. When the accelerometer experiences an acceleration, the mass is displaced to the point that the spring is able to accelerate the mass at the same rate as the casing. The displacement is then measured to give the acceleration.

In commercial devices, piezoelectric, piezoresistive and capacitive components are commonly used to convert the mechanical motion into an electrical signal. Piezoelectric accelerometers rely on piezoceramics (e.g. lead zirconate titanate) or single crystals (e.g. quartz, tourmaline). They are unmatched in terms of their upper frequency range, low packaged weight and high temperature range. Piezoresistive accelerometers are preferred in high shock applications. Capacitive accelerometers typically use a silicon micro-machined sensing element. Their performance is superior in the low frequency range and they can be operated in servo mode to achieve high stability and linearity.

Modern accelerometers are often small *micro electro-mechanical systems* (MEMS), and are indeed the simplest MEMS devices possible, consisting of little more than a cantilever beam with a proof mass (also known as seismic mass). Damping results from the residual gas sealed in the device. As long as the Q-factor is not too low, damping does not result in a lower sensitivity.

Under the influence of external accelerations the proof mass deflects from its neutral position. This deflection is measured in an analog or digital manner. Most commonly, the capacitance between a set of fixed beams and a set of beams attached to the proof mass is measured. This method is simple, reliable, and inexpensive. Integrating piezoresistors in the springs to detect spring deformation, and thus deflection, is a good alternative, although a few more process steps are needed during the fabrication sequence. For very high sensitivities quantum tunneling is also used; this requires a dedicated process making it very expensive. Optical measurement has been demonstrated on laboratory scale.

Another, far less common, type of MEMS-based accelerometer contains a small heater at the bottom of a very small dome, which heats the air inside the dome to cause it to rise. A thermocouple on the dome determines where the heated air reaches the dome and the deflection off the center is a measure of the acceleration applied to the sensor.

Most micromechanical accelerometers operate *in-plane*, that is, they are designed to be sensitive only to a direction in the plane of the die. By integrating two devices perpendicularly on a single die a two-axis accelerometer can be made. By adding an additional *out-of-plane* device three axes can be measured. Such a combination always has a much lower misalignment error than three discrete models combined after packaging.

Micromechanical accelerometers are available in a wide variety of measuring ranges, reaching up to thousands of *g′*s. The designer must make a compromise between sensitivity and the maximum acceleration that can be measured.

Applications

Engineering

Accelerometers can be used to measure vehicle acceleration. They allow for performance evaluation of both the engine/drive train and the braking systems.

Accelerometers can be used to measure vibration on cars, machines, buildings, process control systems and safety installations. They can also be used to measure seismic activity, inclination, machine vibration, dynamic distance and speed with or without the influence of gravity. Applications for accelerometers that measure gravity, wherein an accelerometer is specifically configured for use in gravimetry, are called gravimeters.

Notebook computers equipped with accelerometers can contribute to the *Quake-Catcher Network* (QCN), a BOINC project aimed at scientific research of earthquakes.

Biology

Accelerometers are also increasingly used in the biological sciences. High frequency recordings of bi-axial or tri-axial acceleration (>10 Hz) allows the discrimination of behavioral patterns while animals are out of sight. Furthermore, recordings of acceleration allow researchers to quantify the rate at which an animal is expending energy in the wild, by either determination of limb-stroke frequency or measures such as overall dynamic body acceleration Such approaches have mostly been adopted by marine scientists due to an inability to study animals in the wild using visual observations, however an increasing number of terrestrial biologists are adopting similar approaches. This device can be connected to an amplifier to amplify the signal.

Industry

Accelerometers are also used for machinery health monitoring of rotating equipment such as pumps, fans, rollers, compressors, and cooling towers,. Vibration monitoring programs are proven to save money, reduce downtime, and improve safety in plants worldwide by detecting conditions such as shaft misalignment, rotor imbalance, gear failure or bearing fault which can lead to costly repairs. Accelerometer vibration data allows the user to monitor machines and detect these faults before the rotating equipment fails. Vibration monitoring programs are utilized in industries such as automotive manufacturing, machine tool applications, pharmaceutical production, power generation and power plants, pulp and paper, food and beverage production, water and wastewater, hydropower, petrochemical and steel manufacturing.

Building and structural monitoring

Accelerometers are used to measure the motion and vibration of a structure that is exposed to dynamic loads. Dynamic loads originate from a variety of sources including:

- Human activities - walking, running, dancing or skipping
- Working machines - inside a building or in the surrounding area
- Construction work - driving piles, demolition, drilling and excavating
- Moving loads on bridges
- Vehicle collisions
- Impact loads - falling debris
- Concussion loads - internal and external explosions
- Collapse of structural elements
- Wind loads and wind gusts
- Air blast pressure
- Loss of support because of ground failure
- Earthquakes and aftershocks

Measuring and recording how a structure responds to these inputs is critical for assessing the safety and viability of a structure. This type of monitoring is called Dynamic Monitoring.

Medical applications

Zoll's AED Plus uses CPR-D•padz which contain an accelerometer to measure the depth of CPR chest compressions.

Within the last several years, Nike, Polar and other companies have produced and marketed sports watches for runners that include footpods, containing accelerometers to help determine the speed and distance for the runner wearing the unit.

In Belgium, accelerometer-based step counters are promoted by the government to encourage people to walk a few thousand steps each day.

Herman Digital Trainer uses accelerometers to measure strike force in physical training.

Navigation

An **Inertial Navigation System** (INS) is a navigation aid that uses a computer and motion sensors (accelerometers) to continuously calculate via dead reckoning the position, orientation, and velocity (direction and speed of movement) of a moving object without the need for external references. Other terms used to refer to inertial navigation systems or closely related devices include **inertial guidance system**, **inertial reference platform**, and many other variations.

An accelerometer alone is unsuitable to determine changes in altitude over distances where the vertical decrease of gravity is significant, such as for aircraft and rockets. In the presence of a gravitational gradient, the calibration and data reduction process is numerically unstable.

Transport

Accelerometers are used to detect apogee in both professional and in amateur rocketry.

Accelerometers are also being used in Intelligent Compaction rollers. Accelerometers are used alongside gyroscopes in inertial guidance systems.

One of the most common uses for MEMS accelerometers is in airbag deployment systems for modern automobiles. In this case the accelerometers are used to detect the rapid negative acceleration of the vehicle to determine when a collision has occurred and the severity of the collision. Another common automotive use is in electronic stability control systems, which use a lateral accelerometer to measure cornering forces. The widespread use of accelerometers in the automotive industry has pushed their cost down dramatically. Another automotive application is the monitoring of noise, vibration and harshness (NVH), conditions that cause discomfort for drivers and passengers and may also be indicators of mechanical faults.

Tilting trains use accelerometers and gyroscopes to calculate the required tilt.

Vulcanology

Modern electronic accelerometers are used in remote sensing devices intended for the monitoring of active volcanos to detect the motion of magma

Consumer electronics

Accelerometers are increasingly being incorporated into personal electronic devices.

Motion input

Some smartphones, digital audio players and personal digital assistants contain accelerometers for user interface control; often the accelerometer is used to present landscape or portrait views of the device's screen, based on the way the device is being held.

Smartphones can download an Automatic Collision Notification (ACN) app such as My-911, similar to the Onstar AACN service, Ford Link's 911 Assist, Toyota's Safety Connect, Lexus Link, or BMW Assist. The phone's accelerometer detects crash-strength G-forces and automatically calls for assistance unless manually cancelled.

Nintendo's Wii video game console uses a controller called a Wii Remote that contains a three-axis accelerometer and was designed primarily for motion input. Users also have the option of buying an additional motion-sensitive attachment, the Nunchuk, so that motion input could be recorded from both of the user's hands independently.

The Sony PlayStation 3 uses the DualShock 3 remote which uses a six-axis accelerometer that can be used to make steering more realistic in racing games, such as Motorstorm and Burnout Paradise.

The Nokia 5500 sport features a 3D accelerometer that can be accessed from software. It is used for step recognition (counting) in a sport application, and for tap gesture recognition in the user interface. Tap gestures can be used for controlling the music player and the sport application, for example to change to next song by tapping through clothing when the device is in a pocket. Other uses for accelerometer in Nokia phones include Pedometer functionality in Nokia Sports Tracker. Some other devices provide the tilt sensing feature with a cheaper component, which is not a true accelerometer.

Sleep phase alarm clocks use accelerometric sensors to detect movement of a sleeper, so that it can wake the person when he/she is not in REM phase, therefore awakes more easily.

Orientation sensing

A number of 21st century devices use accelerometers to align the screen depending on the direction the device is held, i.e. switching between portrait and landscape modes. Such devices include many tablet PCs and some smartphones and digital cameras.

For example, Apple uses an LIS302DL accelerometer in the iPhone, iPod Touch and the 4th&5th generation iPod Nano allowing the device to know when it is tilted on its side. Third-party developers have expanded its use with fanciful applications such as electronic bobbleheads. The BlackBerry Storm phone was also an early user of this orientation sensing feature.

The Nokia N95 and Nokia N82 have accelerometers embedded inside them. It was primarily used as a tilt sensor for tagging the orientation to photos taken with the built-in camera, later thanks to a firmware update it became available to other applications.

As of January 2009, almost all new mobile phones and digital cameras contain at least a tilt sensor (sometimes an accelerometer) for the purpose of auto image rotation, motion-sensitive mini-games, and to correct shake when taking photographs.

Image stabilization

Camcorders use accelerometers for image stabilization. Still cameras use accelerometers for anti-blur capturing. The camera holds off snapping the CCD "shutter" when the camera is moving. When the camera is still (if only for a millisecond, as could be the case for vibration), the CCD is "snapped". An example application which has used such technology is the Glogger VS2, a phone application which runs on Symbian OS based phone with accelerometer such as Nokia N96. Some digital cameras, contain accelerometers to determine the orientation of the photo being taken and also for rotating the current picture when viewing.

Device integrity

Many laptops feature an accelerometer which is used to detect drops. If a drop is detected, the heads of the hard disk are parked to avoid data loss and possible head or disk damage by the ensuing shock.

Gravimetry

A **gravimeter** or gravitometer, is an instrument used in gravimetry for measuring the local gravitational field. A gravimeter is a type of accelerometer, except that accelerometers are susceptible to all vibrations including noise, that cause oscillatory accelerations. This is counteracted in the gravimeter by integral vibration isolation and signal processing. Though the essential principle of design is the same as in accelerometers, gravimeters are typically designed to be much more sensitive than accelerometers in order to measure very tiny changes within the Earth's gravity, of 1 *g*. In contrast, other accelerometers are often designed to measure 1000 *g* or more, and many perform multi-axial measurements. The constraints on temporal resolution are usually less for gravimeters, so that resolution can be increased by processing the output with a longer "time constant".

Chapter 7

Fiber Bragg Grating

A **fiber Bragg grating** (**FBG**) is a type of distributed Bragg reflector constructed in a short segment of optical fiber that reflects particular wavelengths of light and transmits all others. This is achieved by adding a periodic variation to the refractive index of the fiber core, which generates a wavelength specific dielectric mirror. A fiber Bragg grating can therefore be used as an inline optical filter to block certain wavelengths, or as a wavelength-specific reflector.

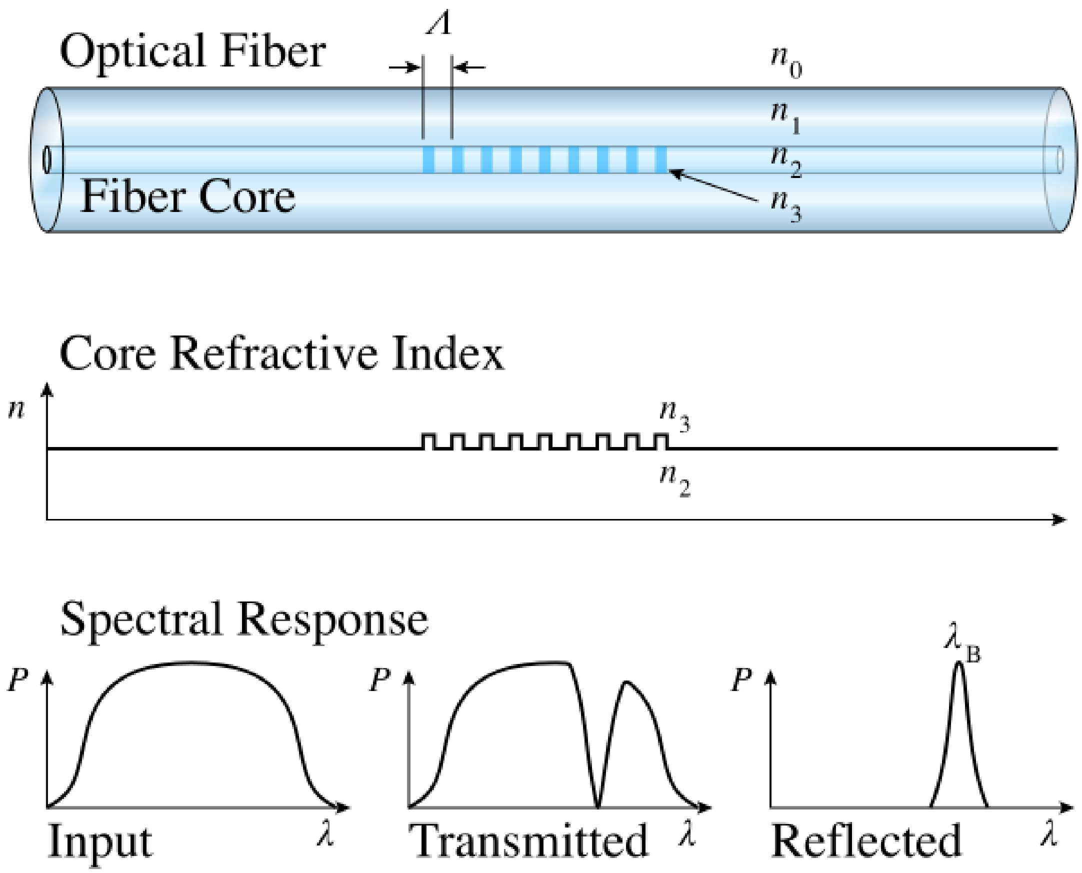


Figure 1: A Fiber Bragg Grating structure, with refractive index profile and spectral response

History

The first in-fiber Bragg grating was demonstrated by Ken Hill in 1978. Initially, the gratings were fabricated using a visible laser propagating along the fiber core. In 1989, Gerald Meltz and colleagues demonstrated the much more flexible transverse holographic technique where the laser illumination came from the side of the fiber. This technique uses the interference pattern of ultraviolet laser light to create the periodic structure of the Bragg grating.

Manufacture

Fiber Bragg gratings are created by "inscribing" or "writing" systematic (periodic or aperiodic) variation of refractive index into the core of a special type of optical fiber using an intense ultraviolet (UV) source such as a UV laser. Two main processes are used: *interference* and *masking*. The method that is preferable depends on the type of grating to be manufactured. A special germanium-doped silica fiber is used in the manufacture of fiber Bragg gratings. The germanium-doped fiber is photosensitive, in that the refractive index of the core changes with exposure to UV light, with the amount of the change a function of the intensity and duration of the exposure.

Interference

The first manufacturing method, specifically used for uniform gratings, is the use of two-beam interference. Here the UV laser is split into two beams which interfere with each other creating a periodic intensity distribution along the interference pattern. The refractive index of the photosensitive fiber changes according to the intensity of light that it is exposed to. This method allows for quick and easy changes to the Bragg wavelength, which is directly related to the interference period and a function of the incident angle of the laser light.

Photomask

A photomask having the intended grating features may also be used in the manufacture of fiber Bragg gratings. The photomask is placed between the UV light source and the photosensitive fiber. The shadow of the photomask then determines the grating structure based on the transmitted intensity of light striking the fiber. Photomasks are specifically used in the manufacture of chirped Fiber Bragg gratings, which cannot be manufactured using an interference pattern.

Point-by-point

A single UV laser beam may also be used to 'write' the grating into the fiber point-by-point. Here, the laser has a narrow beam that is equal to the grating period. This method is specifically applicable to the fabrication of long period fiber gratings. Point-by-point is also used in the fabrication of tilted gratings.

Production

Originally, the manufacture of the photosensitive optical fiber and the 'writing' of the fiber Bragg grating were done separately. Today, production lines typically draw the fiber from the preform and 'write' the grating, all in a single stage. As well as reducing associated costs and time, this also enables the mass production of fiber Bragg gratings. Mass production is in particular facilitating applications in smart structures utilizing large numbers (3000) of embedded fiber Bragg gratings along a single length of fiber.

Theory

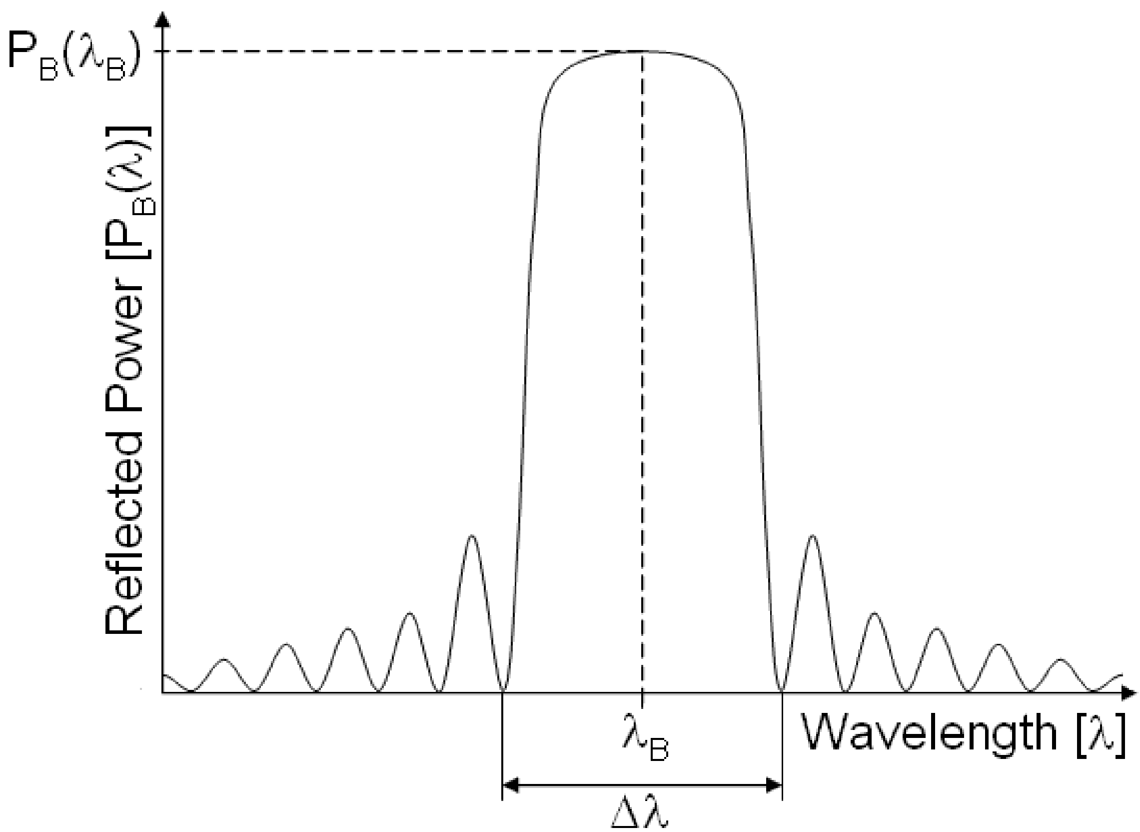


Figure 2: FBGs reflected power as a function of wavelength

The fundamental principle behind the operation of a FBG, is Fresnel reflection. Where light traveling between media of different refractive indices may both reflect and refract at the interface.

The grating will typically have a sinusoidal refractive index variation over a defined length. The reflected wavelength (λ_B), called the Bragg wavelength, is defined by the relationship,

$$\lambda_B = 2n_e\Lambda,$$

where n_e is the effective refractive index of the grating in the fiber core and Λ is the grating period. The effective refractive index quantifies the velocity of propagating light as compared to its velocity in vacuum. n_e depends not only on the wavelength but also (for multimode waveguides) on the mode in which the light propagates. For this reason, it is also called modal index.

The wavelength spacing between the first minima (nulls, see Fig. 2), or the bandwidth (Δλ), is given by,

$$\Delta\lambda = \left[\frac{2\delta n_0 \eta}{\pi}\right]\lambda_B,$$

where δn_0 is the variation in the refractive index ($n_3 - n_2$), and η is the fraction of power in the core.

The peak reflection ($P_B(\lambda_B)$) is approximately given by,

$$P_B(\lambda_B) \approx \tanh^2\left[\frac{N\eta(V)\delta n_0}{n}\right],$$

where N is the number of periodic variations. The full equation for the reflected power ($P_B(\lambda)$), is given by,

$$P_B(\lambda) = \frac{\sinh^2\left[\eta(V)\delta n_0\sqrt{1-\Gamma^2}N\Lambda/\lambda\right]}{\cosh^2\left[\eta(V)\delta n_0\sqrt{1-\Gamma^2}N\Lambda/\lambda\right]-\Gamma^2},$$

where,

$$\Gamma(\lambda) = \frac{1}{\eta(V)\delta n_0}\left[\frac{\lambda}{\lambda_B}-1\right].$$

Types of gratings

The term "type" in this context refers to the underlying photosensitivity mechanism by which grating fringes are produced in the fiber. The different methods of creating these fringes have a significant effect on physical attributes of the produced grating, particularly the temperature response and ability to withstand elevated temperatures. Thus far, five (or six) types of FBG have been reported with different underlying photosensitivity mechanisms. These are summarized below:

Standard gratings or Type I gratings

Written in both hydrogenated and non-hydrogenated fiber of all types Type I gratings are usually known as standard gratings and are manufactured in fibers of all types under all hydrogenation conditions. Typically, the reflection spectra of a type I grating is equal to 1-T where T is the transmission spectra. This means that the reflection and transmission spectra are complementary and there is negligible loss of light by reflection into the cladding or by absorption. Type I gratings are the most commonly used of all grating types, and the only types of grating available off-the-shelf at the time of writing.

Type IA gratings

- Regenerated grating written after erasure of a type I grating in hydrogenated germanosilicate fiber of all types

Type IA gratings were first published in 2001 during experiments designed to determine the effects of hydrogen loading on the formation of IIA gratings in germanosilicate fiber. In contrast to the anticipated blue shift of the peak Bragg wavelength, a large positive wavelength shift was measured. This type IA grating appeared once the conventional type I FBG had reached saturation followed by subsequent complete or partial erasure, and was therefore labeled as regenerated. It was also noted that the temperature coefficient of the regenerated grating was lower than a standard grating written under similar conditions.

There is a clear relationship between type IA and IIA gratings insomuch as their fabrication conditions are identical in all but one aspect: they both form in B/Ge co-doped fiber but IAs form only in hydrogenated fibers and IIAs form only in non-hydrogenated fibers.

Type In (commonly known as Type IIA gratings)

- These are gratings that form as the negative part of the induced index change overtakes the positive part. It is usually associated with gradual relaxation of induced stress along the axis and/or at the interface. These gratings have recently been relabeled Type In (for Type 1 gratings with a negative index change; Type II label is reserved for those that are distinctly made above the damage threshold of the glass).

Later research by Xie et al. showed the existence of another type of grating with similar thermal stability properties to the type II grating. This grating exhibited a negative change in the mean index of the fiber and was termed type IIA. The gratings were formed in germanosilicate fibers with pulses from a frequency doubled XeCl pumped dye laser. It was shown that initial exposure formed a standard (type I) grating within the fiber which underwent a small red shift before being erased. Further exposure showed that a grating reformed which underwent a steady blue shift whilst growing in strength.

Regenerated gratings

These are gratings that are reborn at higher temperatures after erasure of gratings, usually Type I gratings and usually, though not always, in the presence of hydrogen. They have been interpreted in different ways including dopant diffusion (oxygen being the most popular current interpretation) and glass structural change. Recent work has shown that there exists a regeneration regime beyond diffusion where gratings can be made to operate at temperatures in excess of 1295C, outperforming even Type II femtosecond gratings. These are extremely attractive for ultra high temperature applications.

Type II gratings

- Damage written gratings inscribed by multiphoton excitation with higher intensity lasers that exceed the damage threshold of the glass. Lasers employed are usually pulsed in order to reach these intensities. They include recent developments in multiphoton excitation using femtosecond pulses where the short timescales (commensurate on a timescale similar to local relaxation times) offer unprecedented spatial localization of the induced change. The amorphous network of the glass is usually transformed via a different ionization and melting pathway to give either higher index changes or create, through micro-explosions, voids surrounded by more dense glass.

Archambault et al. showed that it was possible to inscribe gratings of ~100% (>99.8%) reflectance with a single UV pulse in fibers on the draw tower. The resulting gratings were shown to be stable at temperatures as high as 800˚C (up to 1000C in some cases, and higher with femtosecond laser inscription). The gratings were inscribed using a single 40mJ pulse from an excimer laser at 248 nm. It was further shown that a sharp threshold was evident at ~30mJ; above this level the index modulation increased by more than two orders of magnitude, whereas below 30mJ the index modulation grew linearly with pulse energy. For ease of identification, and in recognition of the distinct differences in thermal stability, they labeled gratings fabricated below the threshold as type I gratings and above the threshold as type II gratings. Microscopic examination of these gratings showed a periodic damage track at the grating's site within the fiber ; hence type II gratings are also known as damage gratings. However, these cracks can be very localized so as to not play a major role in scattering loss if properly prepared

Grating structure

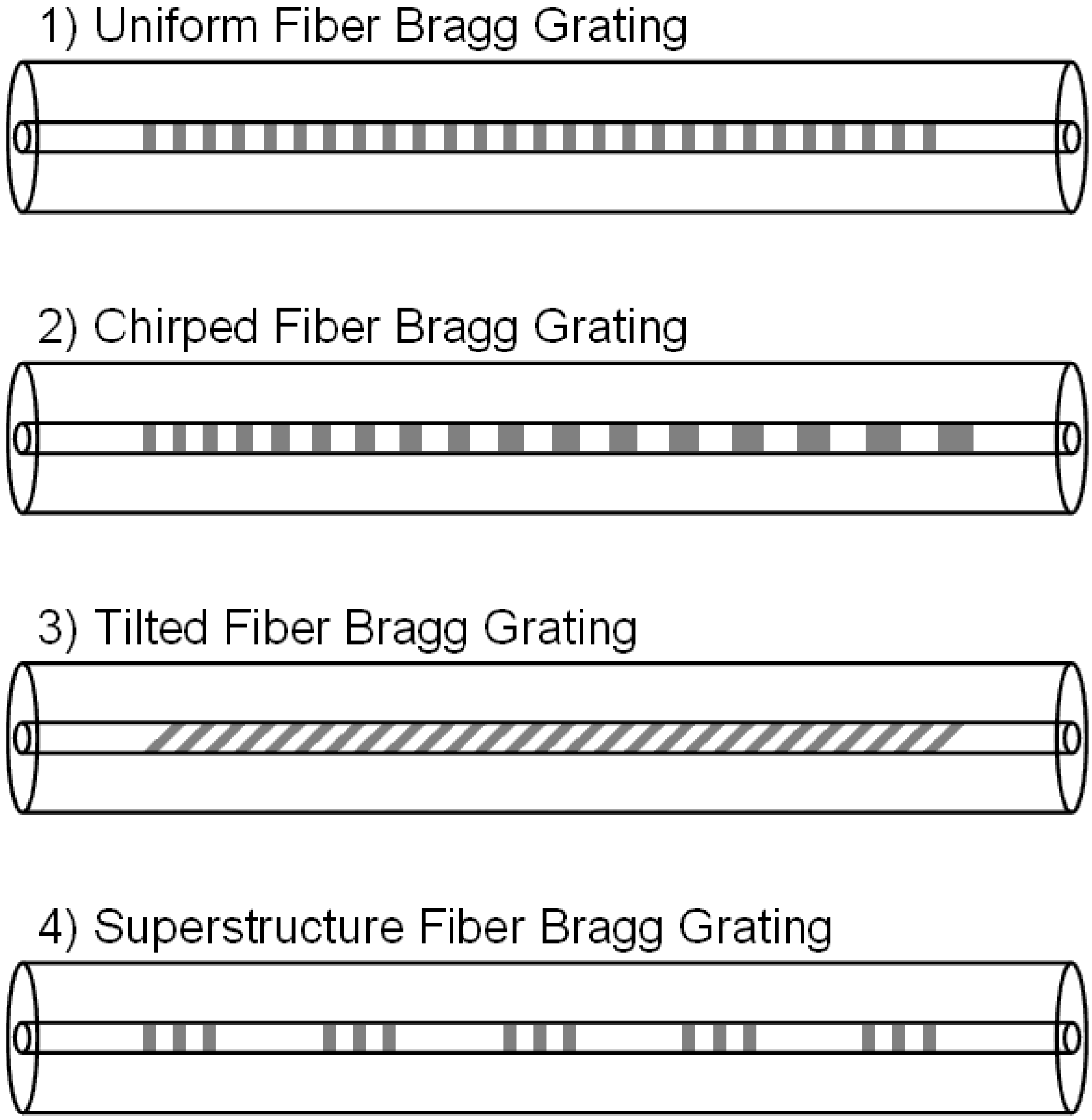


Figure 3: Structure of the refractive index change in a uniform FBG (1), a chirped FBG (2), a tilted FBG (3), and a superstructure FBG (4).

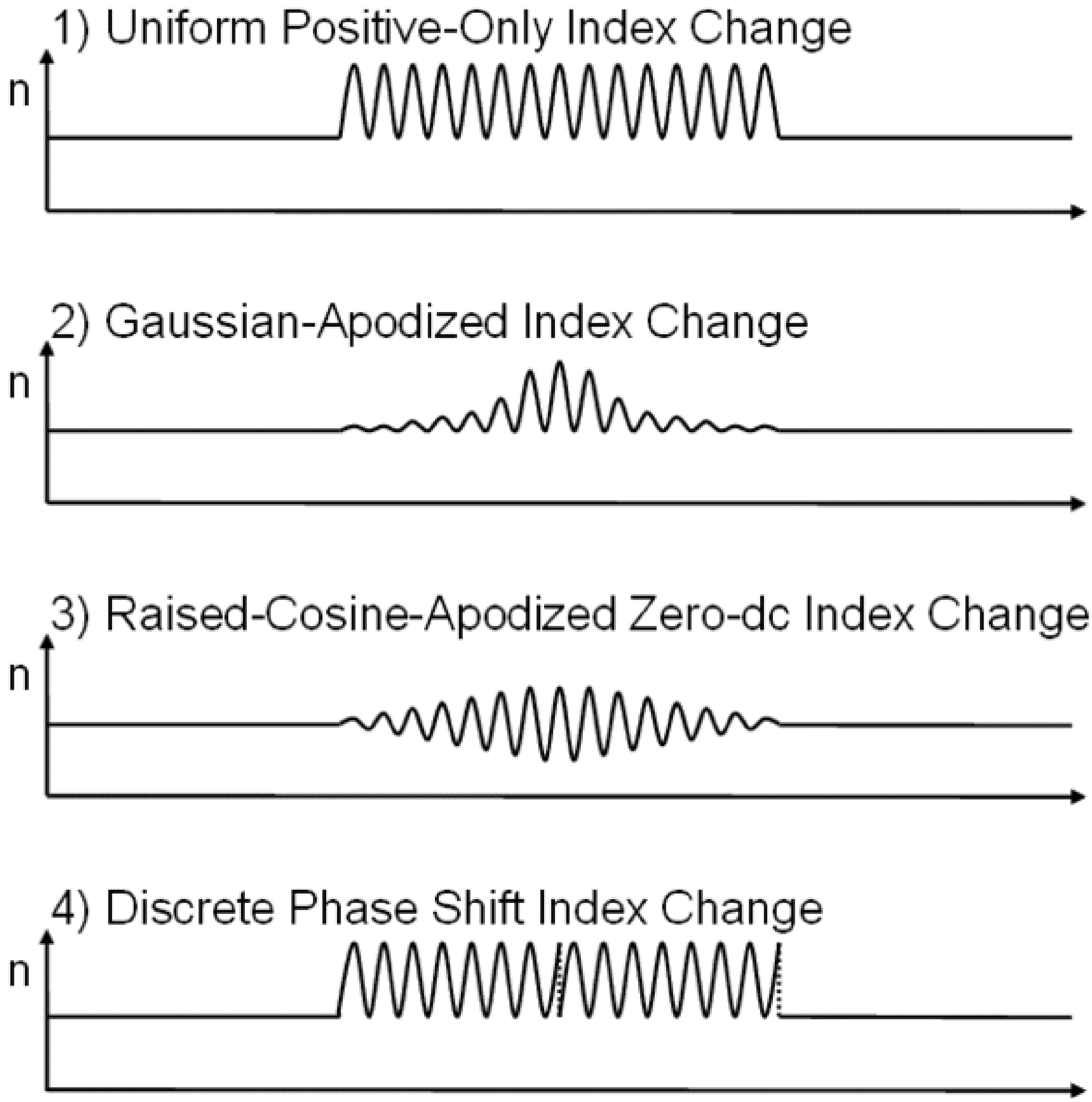


Figure 4: Refractive index profile in the core of, 1) a uniform positive-only FBG, 2) a Gaussian-apodized FBG, 3) a raised-cosine-apodized FBG with zero-dc change, and 4) a discrete phase shift FBG.

The structure of the FBG can vary via the refractive index, or the grating period. The grating period can be uniform or graded, and either localised or distributed in a superstructure. The refractive index has two primary characteristics, the refractive index profile, and the offset. Typically, the refractive index profile can be uniform or apodized, and the refractive index offset is positive or zero.

There are six common structures for FBGs;

1. uniform positive-only index change,
2. Gaussian apodized,

3. raised-cosine apodized,
4. chirped,
5. discrete phase shift, and
6. superstructure.

The first complex grating was made by J. Canning in 1994. This supported the development of the first distributed feedback (DFB) fiber lasers, and also laid the groundwork for most complex gratings that followed, including the sampled gratings first made by Peter Hill and colleagues in Australia.

Apodized gratings

There are basically two quantities that control the properties of the FBG. These are the grating length, L_g, given as

$$L_g = N\Lambda,$$

and the grating strength, $\delta n_0\ \eta$. There are, however, three properties that need to be controlled in a FBG. These are the reflectivity, the bandwidth, and the side-lobe strength. As shown above, the bandwidth depends on the grating strength, and not the grating length. This means the grating strength can be used to set the bandwidth. The grating length, effectively *N*, can then be used to set the peak reflectivity, which depends on both the grating strength and the grating length. The result of this is that the side-lobe strength cannot be controlled, and this simple optimisation results in significant side-lobes. A third quantity can be varied to help with side-lobe suppression. This is apodization of the refractive index change. The term apodization refers to the grading of the refractive index to approach zero at the end of the grating. Apodized gratings offer significant improvement in side-lobe suppression while maintaining reflectivity and a narrow bandwidth. The two functions typically used to apodize a FBG are Gaussian and raised-cosine.

Chirped fiber Bragg gratings

The refractive index profile of the grating may be modified to add other features, such as a linear variation in the grating period, called a chirp. The reflected wavelength changes with the grating period, broadening the reflected spectrum. A grating possessing a chirp has the property of adding dispersion—namely, different wavelengths reflected from the grating will be subject to different delays. This property has been used in the development of phased-array antenna systems and polarization mode dispersion compensation, as well.

Tilted fiber Bragg gratings

In standard FBGs, the grading or variation of the refractive index is along the length of the fiber (the optical axis), and is typically uniform across the width of the fiber. In a tilted FBG (TFBG), the variation of the refractive index is at an angle to the optical axis. The angle of tilt in a TFBG has an effect on the reflected wavelength, and bandwidth.

Long-period gratings

Typically the grating period is the same size as the Bragg wavelength, as shown above. For a grating that reflects at 1500 nm, the grating period is 500 nm, using a refractive index of 1.5. Longer periods can be used to achieve much broader responses than are possible with a standard FBG. These gratings are called long-period fiber grating. They typically have grating periods on the order of 100 micrometers, to a millimeter, and are therefore much easier to manufacture.

Applications

Communications

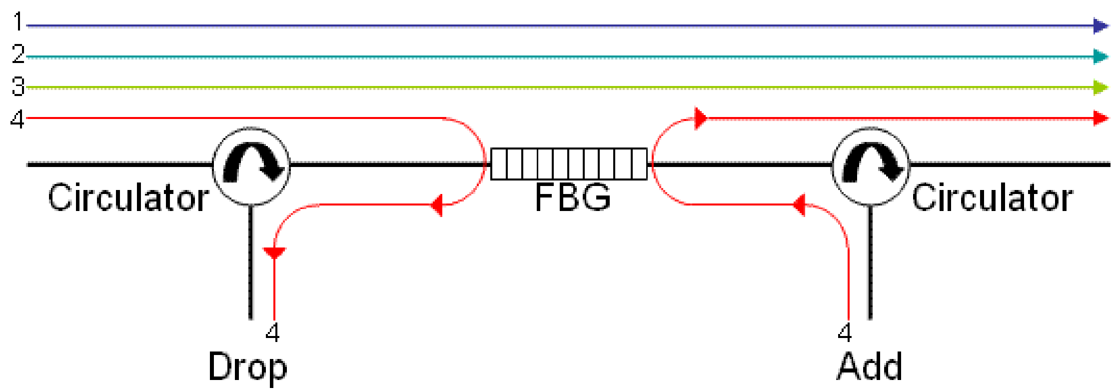


Figure 5: Optical add-drop multiplexer.

The primary application of fiber Bragg gratings is in optical communications systems. They are specifically used as notch filters. They are also used in optical multiplexers and demultiplexers with an optical circulator, or Optical Add-Drop Multiplexer (OADM). Figure 5 shows 4 channels, depicted as 4 colours, impinging onto a FBG via an optical circulator. The FBG is set to reflect one of the channels, here channel 4. The signal is reflected back to the circulator where it is directed down and dropped out of the system. Since the channel has been dropped, another signal on that channel can be added at the same point in the network.

A demultiplexer can be achieved by cascading multiple drop sections of the OADM, where each drop element uses a FBG set to the wavelength to be demultiplexed. Conversely, a multiplexer can be achieved by cascading multiple add sections of the OADM. FBG demultiplexers and OADMs can also be tunable. In a tunable demultiplexer or OADM, the Bragg wavelength of the FBG can be tuned by strain applied by a piezoelectric transducer. The sensitivity of a FBG to strain is discussed below in fiber Bragg grating sensors.

Fiber Bragg grating sensors

As well as being sensitive to strain, the Bragg wavelength is also sensitive to temperature. This means that fiber Bragg gratings can be used as sensing elements in optical fiber sensors. In a FBG sensor, the measurand causes a shift in the Bragg wavelength, $\Delta\lambda_B$. The relative shift in the Bragg wavelength, $\Delta\lambda_B / \lambda_B$, due to an applied strain (ε) and a change in temperature (ΔT) is approximately given by,

$$\left[\frac{\Delta\lambda_B}{\lambda_B}\right] = C_S\epsilon + C_T\Delta T,$$

or,

$$\left[\frac{\Delta\lambda_B}{\lambda_B}\right] = (1 - p_e)\epsilon + (\alpha_\Lambda + \alpha_n)\Delta T.$$

Here, C_S is the *coefficient of strain*, which is related to the *strain optic coefficient* p_e. Also, C_T is the *coefficient of temperature*, which is made up of the *thermal expansion coefficient* of the optical fiber, α_Λ, and the *thermo-optic coefficient*, α_n.

Fiber Bragg gratings can then be used as direct sensing elements for strain and temperature. They can also be used as transduction elements, converting the output of another sensor, which generates a strain or temperature change from the measurand, for example fiber Bragg grating gas sensors use an absorbent coating, which in the presence of a gas expands generating a strain, which is measurable by the grating. Technically, the absorbent material is the sensing element, converting the amount of gas to a strain. The Bragg grating then transduces the strain to the change in wavelength.

Specifically, fiber Bragg gratings are finding uses in instrumentation applications such as seismology, pressure sensors for extremely harsh environments, and as downhole sensors in oil and gas wells for measurement of the effects of external pressure, temperature, seismic vibrations and inline flow measurement. As such they offer a significant advantage over traditional electronic gauges used for these applications in that they are less sensitive to vibration or heat and consequently are far more reliable. In the 1990s, investigations were conducted for measuring strain and temperature in composite materials for aircraft and helicopter structures.

Chapter 8

Cellular Confinement

Cellular Confinement Systems (CCS, also known as **geocells**) are widely used in construction for erosion control, soil stabilization on flat ground and steep slopes, channel protection, and structural reinforcement for load support and earth retention. Typical cellular confinement systems are made with ultrasonically-welded high-density polyethylene (HDPE) or other polymeric alloy strips that are expanded on-site to form a honeycomb-like structure which may be filled with sand, soil, rock or concrete.

History of Cellular Confinement

Research and development of cellular confinement systems (CCS) began with the U.S. Army Corps of Engineers in September 1975 to test the feasibility of constructing tactical bridge approach roads over soft ground. Engineers discovered that sand-confinement systems performed better than conventional crushed stone sections. They concluded that a sand-confinement system could be developed that would provide an expedient construction technique for building approach roads over soft ground and that the system would not be adversely affected by wet weather conditions. These early efforts led to the civilian commercialization of the product by the Presto Products Company. to produce the first cellular confinement system from high density polyethylene (HDPE) that was light weight, strong and durable. This new cellular confinement system was used first for load support applications in the United States in the early 1980s; second for slope erosion control and channel lining in the United States in 1984 and; third for earth retention in Canada in 1986. Research on cellular confinement in these application areas also started during the 1980s.

Research by Drs. Bathurst and Jarrett discovered that cellular confinement reinforced gravel bases are “equivalent to about twice the thickness of unreinforced gravel bases” when placed over a saturated peat sub-base. Further, 1.25 mm (50 mil) HDPE performed better than single sheet reinforcement schemes (geotextiles and geogrids) and was more effective in reducing lateral spreading of the infill material under loading than conventional reinforced bases. In terms of the effectiveness of confinement, geocells have more attractive features due to its 3D structure than any other planar geosynthetic reinforcement. Since this early work, the results of large-scale triaxial test on isolated geocells has demonstrated that cellular confinement imparts apparent cohesion to cohesionless compacted granular material on the order of 169 kPa - 190 kPa (3500 psf - 4000 psf). Cellular confinement systems are now recognized as an important technology when applied to load support (Webster, 1986 and Bathurst & Jarrett, 1988) under roads and rail lines, gravity and reinforced earth retaining wall systems (Crowe, Bathurst & Alston, 1989), (Bathurst, Crowe & Zehaluk, 1993), slope stabilization and erosion control, channel lining systems (Engel, P. & Flato, G. 1987) (Simons, Li & Associates, 1988) (Wu & Austin, 1992) and other innovative uses.

From HDPE to new polymeric alloys

Competition in the business has led to questionable assertions to differentiate cellular confinement materials. While traditional HDPE based geocells may deform in small measure plastically over time, questions about their effectiveness for long-term reinforcement are for the most part overstated, because although geocells from advanced polymeric alloys can provide stiffness and confinement, they do not enable new, critical applications. Tens of thousands of installations without failure are in service - many for over thirty years. However, newcomers to the industry are attempting to create concerns about long standing standards of performance. The untested systems have focused on the development of advanced polymeric alloys that claim exponentially higher fatigue limits and resistance to environmental factors, particularly high temperatures well over 120 degrees F. Such properties mean very little as cellular confinement never reach such high temperatures as they are buried into the earth in their applications. Of course, it is understood by knowledgeable Engineers that even in the heat of the summer day, the earth remains relatively cool. Therefore, The so called alloys have no real additional benefit beyond those made of HDPE. Further, such "alloys" are made from less expensive materials and allow for less flexibility of finished product creating some problems for installations crews in cool climates. More predictable and reliable performance is not generally found from advanced polymeric alloy.

How it works

A Cellular Confinement System when infilled with compacted soil creates a new composite entity that possesses enhanced mechanical and geotechnical properties. When the soil contained within a geocell is subjected to pressure, it causes lateral stresses on perimeter cell walls. The 3D zone of confinement reduces the lateral movement of soil particles while vertical loading on the contained infill results in high lateral stress and resistance on the cell-soil interface. These increase the shear strength of the confined soil, which:

- Creates a stiff mattress or slab to distribute the load over a wider area
- Reduces punching of soft soil
- Increases shear resistance and bearing capacity
- Decreases deformation

Confinement from adjacent cells provides additional resistance against the loaded cell through passive resistance, while lateral expansion of the infill is restricted by high hoop strength. Compaction is maintained by the confinement resulting in long term reinforcement.

Applications

Load Support

Cellular Confinement Systems (CCS) have been used to improve the performance of both paved and unpaved roads by reinforcing the soil in the subgrade-base interface or within the base course. The effective load distribution of CCS creates a strong, stiff cellular mattress. This 3D mattress reduces vertical differential settlement into soft subgrades, improves shear strength, and enhances load-bearing capacity, while reducing the amount of aggregate material required to extend the service life of roads. As a composite system, cellular confinement strengthens the aggregate infill, thereby simultaneously enabling the use of poorly graded inferior material (e.g. local native soils, quarry waste or recycled materials) for infill as well as reducing the structural support layer thickness. Typical load support applications include reinforcement of base and subbase layers in flexible pavements, including: asphalt pavements; unpaved access, service and haul roads; railway substructure and ballast confinement; working platforms in intermodal ports; airport runways and aprons, permeable pavements; pipeline road support; green parking facilities and emergency access areas.

Slope and Channel Protection

The three-dimensional lateral confinement of CCS along with anchoring techniques ensures the long-term stability of slopes using vegetated topsoil, aggregate or concrete surfacing (if exposed to severe mechanical and hydraulic pressures). The enhanced drainage, frictional forces and cell-soil-plant interaction of CCS prevents downslope movement and limits the impact of raindrops, channeling and hydraulic shear stresses. The perforations in the 3D cells allow the passage of water, nutrients and soil organisms. This encourages plant growth and root interlock, which further stabilizes the slope and soil mass, and facilitates landscape rehabilitation. Typical applications include: construction cut and fill slopes and stabilization; road and rail embankments; pipeline stabilization and storage facility berms; quarry and mine site restoration; channel and coastline structures.

Earth Retention

CCS systems provide steep vertical mechanically stabilized earth structures (either gravity or reinforced walls) for steep faces, walls and irregular topography. Construction of CCS earth retention is simiplified as each layer is structurally sound thereby providing access for equipment and workers, while eliminating the need for concrete formwork and curing. Local soil can be used for infill, while the outer faces enable a green or tan fascia of the horizontal terraces/rows. In addition research by Leshchinsky, D. (2009) has demonstrated superior seismic stability of CCS systems in earthquake simulation tests.

Reservoirs and Landfills

CCS provides membrane liner protection, while creating stable soil, berms and slopes, for non-slip protection and durable impoundment of liquids and waste. Infill treatment depends on the contained materials: concrete for ponds and reservoirs; gravel for landfill drainage and leachates, vegetated infill for landscape rehabilitation. Concrete work is efficient and controlled as CCS functions as ready-made forms; CCS with concrete forms a flexible slab that accommodates minor subgrade movement and prevents cracking. In medium and low flow-velocities, CCS with geomembranes and gravel cover can be used to create impermeable channels, thereby eliminating the need for concrete.

Sustainable Construction

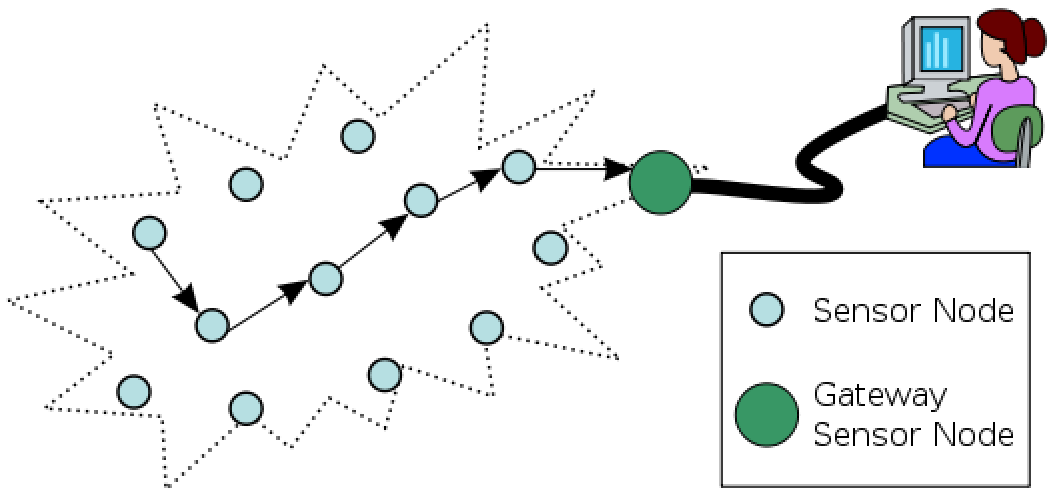
CCS is a green solution that makes civil infrastructure projects more sustainable. In load support applications, by reducing the amount and type of infill needed to reinforce soil, the usage of haul and earthmoving equipment is reduced. This in turn decreases fuel use, pollution and the carbon footprint, and at the same time minimizes on-site disruption from dust, erosion and runoff. When used for slope applications, perforated geocells provides excellent soil protection, water drainage and growth stratum for plants. The long-term design life of advanced CCS technology means that maintenance and the associated environmental costs are significantly reduced, as are long-term economic costs.

Research

In the field and laboratory tests, CCS has proven to significantly increase the lifetime of the pavement and decrease road and railway substructure maintenance. Research on cellular confinement in these application areas focused on three ways: 1) use of triaxial or resilient modulus cells to investigate the confinement effect on apparent cohesion or reducing plastic deformation; 2) the use of laboratory model tests to investigate the reinforcement effect on bearing capacity and reducing settlement under static or dynamic loading; and 3) full-scale trafficking tests to investigate the overall effect, as reducing rut depth and prolonging road life. An extensive review of existing literature on 26 CCS research studies including triaxial compression tests, laboratory model tests, and field tests, researchers concluded that: 1) Geocell reinforced bases always performed better than unreinforced bases with the same thickness in terms of the bearing capacity under static and repeated loading; 2) Proper tensile and seam strengths are needed for geocells to provide effective reinforcement. Geocells made of high strength materials typically had higher bearing capacity; 3) There exist optimum values of the geocell height/width ratio and the loading area width/geocell width ratio; 4) Geocells showed excellent performance as compared with 2D planar reinforcement; 5) High-quality infill materials yield high bearing capacity of geocell-reinforced bases.

Chapter 9

Wireless Sensor Network



Typical Multihop Wireless Sensor Network Architecture

A **Wireless Sensor Network** (WSN) consists of spatially distributed autonomous sensors to *monitor* physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants., and to cooperatively pass their data through the network to a main location. The more modern networks are bi-directional, enabling also to *control* the activity of the sensors. The development of wireless sensor networks was motivated by military applications such as battlefield surveillance; today such networks are used in many industrial and consumer application, such as industrial process monitoring and control, machine health monitoring, environment and habitat monitoring, healthcare applications, home automation, and traffic control.

The WSN is built of "nodes" - from a few to several hundreds or even thousands, where each node is connected to one (or sometimes several) sensors. Each such sensor network node has typically several parts: a radio transceiver with an internal antenna or connection to an external antenna, a microcontroller, an electronic circuit for interfacing with the sensors and an energy source, usually a battery or an embedded form of energy harvesting. A sensor node might vary in size from that of a shoebox down to the size of a grain of dust, although functioning "motes" of genuine microscopic dimensions have yet to be created. The cost of sensor nodes is similarly variable, ranging from hundreds of dollars to a few pennies, depending on the complexity of the individual sensor nodes. Size and cost constraints on sensor nodes result in corresponding constraints on resources such as energy, memory, computational speed and communications bandwidth.. The topology of the WSNs can vary from a simple star network to an advanced multi-hop wireless mesh network. The propagation technique between the hops of the network can be routing or flooding.

In computer science and telecommunications, wireless sensor networks are an active research area with numerous workshops and conferences arranged each year.

Area monitoring

Area monitoring is a common application of WSNs. In area monitoring, the WSN is deployed over a region where some phenomenon is to be monitored. A military example is the use of sensors to detect enemy intrusion; a civilian example is the geo-fencing of gas or oil pipelines.

When the sensors detect the event being monitored (heat, pressure), the event is reported to one of the base stations, which then takes appropriate action (e.g., send a message on the internet or to a satellite). Similarly, wireless sensor networks can use a range of sensors to detect the presence of vehicles ranging from motorcycles to train cars.

Environmental monitoring

A number of WSNs have been deployed for environmental monitoring.

Air pollution monitoring

Wireless sensor networks have been deployed in several cities (Stockholm, London or Brisbane) to monitor the concentration of dangerous gases for citizens. The sensor nodes can control important parameters like CO, CO2, NO2 or CH4, which are generated by vehicles and industry, and have a severe impact on the human health. This way, the public institutions have a good tool to design plans to reduce pollution, improve the air quality and ensure the compliance with current legislation.

Forest fires detection

A network of Sensor Nodes can be installed in a forest to control when a fire has started. The nodes will be equipped with sensors to control temperature, humidty and gases which are produced by fire in the trees or vegetation. The early detection is crucial for a successful action of the firefighters; thanks to Wireless Sensor Networks, the fire brigade will be able to know when a fire is started and how it is spreading.

Greenhouse monitoring

Wireless sensor networks are also used to control the temperature and humidity levels inside commercial greenhouses. When the temperature and humidity drops below specific levels, the greenhouse manager must be notified via e-mail or cell phone text message, or host systems can trigger misting systems, open vents, turn on fans, or control a wide variety of system responses.

Landslide detection

A landslide detection system, makes use of a wireless sensor network to detect the slight movements of soil and changes in various parameters that may occur before or during a landslide. And through the data gathered it may be possible to know the occurrence of landslides long before it actually happens.

Industrial monitoring

Machine health monitoring

Wireless sensor networks have been developed for machinery condition-based maintenance (CBM)as they offer significant cost savings and enable new functionalities. In wired systems, the installation of enough sensors is often limited by the cost of wiring. Previously inaccessible locations, rotating machinery, hazardous or restricted areas, and mobile assets can now be reached with wireless sensors.

Water/Wastewater monitoring

There are many opportunities for using wireless sensor networks within the water/wastewater industries. Facilities not wired for power or data transmission can be monitored using industrial wireless I/O devices and sensors powered using solar panels or battery packs.

Landfill ground well level monitoring and pump counter

Wireless sensor networks can be used to measure and monitor the water levels within all ground wells in the landfill site and monitor leachate accumulation and removal. A wireless device and submersible pressure transmitter monitors the leachate level. The sensor information is wirelessly transmitted to a central data logging system to store the level data, perform calculations, or notify personnel when a service vehicle is needed at a specific well.

Agriculture

Using wireless sensor networks within the agricultural industry is increasingly common; using a wireless network frees the farmer from the maintenance of wiring in a difficult environment. Gravity feed water systems can be monitored using pressure transmitters to monitor water tank levels, pumps can be controlled using wireless I/O devices, and water use can be measured and wirelessly transmitted back to a central control center for billing. Irrigation automation enables more efficient water use and reduces waste.

Fleet monitoring

It is possible to put a node on-board of each vehicle of a fleet. The node gathers its position via the GPS module, and reports its coordinates so that the location is tracked in real-time. The nodes can be connected to temperature sensors to avoid any disruption of the cold chain, helping to ensure the safety of food, pharmaceutical and chemical shipments. In situations where there is not reliable GPS coverage, like inside buildings, garages and tunnels, using information from GSM cells is an alternative for to GPS localization.

Characteristics

The main characteristics of a WSN include:

- Power consumption constrains for nodes using batteries or energy harvesting
- Ability to cope with node failures
- Mobility of nodes
- Dynamic network topology
- Communication failures
- Heterogeneity of nodes
- Scalability to large scale of deployment
- Ability to withstand harsh environmental conditions
- Easy of use
- Unattended operation.

Sensor nodes can be imagined as small computers, extremely basic in terms of their interfaces and their components. They usually consist of a *processing unit* with limited computational power and limited memory, *sensors* or MEMS (including specific conditioning circuitry), a *communication device* (usually radio transceivers or alternatively optical), and a power source usually in the form of a battery. Other possible inclusions are energy harvesting modules, secondary ASICs, and possibly secondary communication devices (e.g. RS-232 or USB).

The base stations are one or more distinguished components of the WSN with much more computational, energy and communication resources. They act as a gateway between sensor nodes and the end user as they typically forward data from the WSN on to a server. Other special components in routing based networks are routers, designed to compute, calculate and distribute the routing tables. Many techniques are used to connect to the outside world including mobile phone networks, satellite phones, radio modems, high power WiFi links etc.

Platforms

Standards and specifications

Several standards are currently either ratified or under development for wireless sensor networks. There are a number of standardization bodies in the field of WSNs. The IEEE focuses on the physical and MAC layers; the Internet Engineering Task Force works on layers 3 and above. In addition to these, bodies such as the International Society of Automation provide vertical solutions, covering all protocol layer. Finally, there are also several non-standard, proprietary mechanisms and specifications.

Standards are used far less in WSNs than in other computing systems. However predominant standards commonly used in WSN communications include:

- ISA100
- IEEE 1451
- ZigBee / 802.15.4
- IEEE 802.11

Hardware

The main challenge in a WSN is to produce *low cost* and *tiny* sensor nodes. There are an increasing number of small companies producing WSN hardware and the commercial situation can be compared to home computing in the 1970s. Many of the nodes are still in the research and development stage, particularly their software. Also inherent to sensor network adoption is the use very low power method for data acquisition.

Software

Energy is the scarcest resource of WSN nodes, and it determines the lifetime of WSNs. WSNs are meant to be deployed in large numbers in various environments, including remote and hostile regions, with ad-hoc communications as key. For this reason, algorithms and protocols need to address the following issues:

- Lifetime maximization
- Robustness and fault tolerance
- Self-configuration

Some of the important topics in WSN software research are:

- Operating systems
- Security
- Mobility
- Usability - human interface for deployment and management, debugging and end-user control

- Middleware - the design of middle-level primitives between high level software and the systems

Operating systems

Operating systems for wireless sensor network nodes are typically less complex than general-purpose operating systems. They more strongly resemble embedded systems, for two reasons. First, wireless sensor networks are typically deployed with a particular application in mind, rather than as a general platform. Second, a need for low costs and low power leads most wireless sensor nodes to have low-power microcontrollers ensuring that mechanisms such as virtual memory either unnecessary or too expensive to implement.

It is therefore possible to use embedded operating systems such as eCos or uC/OS for sensor networks. However, such operating systems are often designed with real-time properties.

TinyOS is perhaps the first operating system specifically designed for wireless sensor networks. TinyOS is based on an event-driven programming model instead of multithreading. TinyOS programs are composed into *event handlers* and *tasks* with run to completion-semantics. When an external event occurs, such as an incoming data packet or a sensor reading, TinyOS signals the appropriate event handler to handle the event. Event handlers can post tasks that are scheduled by the TinyOS kernel some time later.

LiteOS is a newly developed OS for wireless sensor networks, which provides UNIX like abstraction and support for C programming language. Contiki is an OS which uses a simpler programming style in C while providing advances such as 6LoWPAN and proto-threads.

Algorithms

The *algorithmic* approach to modelling, simulating and analyzing WSNs differentiates itself from the *protocol* approach by the fact that the idealised mathematical models used are more general and easier to analyze. However, they are sometimes less realistic than the models used for protocol design, since an algorithmic approach often neglects timing issues, protocol overhead, the routing initiation phase and sometimes distributed implementation of the algorithms.

Discussion of WSN simulators

There are network simulator platforms specifically designed to model and simulate Wireless Sensor Networks, like TOSSIM, which is a part of TinyOS and COOJA which is a part of Contiki. Traditional network simulators like ns-2 have also been used. Ns-3, which is an upgrade over Ns-2 is expected to be released shortly, also features WSN libraries

Network Simulators like QualNet, Opnet, NetSim and NS2 can be used to simulate Wireless Sensor Network. Other simulators, like IDEA1 -based on SystemC- have hardware-level librairies that permits system-level simulations by taking low-level constraints into account.

Based on Matlab, the Prowler (Probabilistic Wireless Network Simulator) toolbox is available.

Other concepts

Distributed sensor network

If a centralised architecture is used in a sensor network and the central node fails, then the entire network will collapse, however the reliability of the sensor network can be increased by using distributed architecture.
Distributed architecture is used in WSNs for the following reasons:

1. Sensor nodes are prone to failure,
2. For better collection of data
3. To provide nodes with backup in case of failure of the central node

We also take care of nodes sensing redundant information and forwarding the data that is of no use. There is also no centralised body to allocate the resources and they have to be self organised.

Data visualization

The data gathered from wireless sensor networks is usually saved in the form of numerical data in a central base station. Additionally, the Open Geospatial Consortium (OGC) is specifying standards for interoperability interfaces and metadata encodings that enable real time integration of heterogeneous sensor webs into the Internet, allowing any individual to monitor or control Wireless Sensor Networks through a Web Browser.

Information fusion

In wireless sensor networks, information fusion, also called data fusion, has been developed for processing sensor data by filtering, aggregating, and making inferences about the gathered data. Information fusion deals with the combination of multiple sources to obtain improved information: cheaper, greater quality or greater relevance. Within the wireless sensor networks domain, simple aggregation techniques such as maximum, minimum, and average, have been developed for reducing the overall data traffic to save energy.

Chapter 10

Deformation Monitoring & Automatic Deformation Monitoring System

Deformation Monitoring

Deformation monitoring (also referred to as **Deformation survey**) is the systematic measurement and tracking of the alteration in the shape or dimensions of an object as a result of the application of stress to it. Deformation monitoring is a major component of logging measured values that may be used to for further computation, deformation analysis, predictive maintenance and alarming.

Deformation monitoring is primarily related to the field of applied surveying, but may be also related to the civil engineering, mechanical engineering, plant construction, soil and rock sta-bility mechanics.

The causes for deformation monitoring are changes in the bedrock, increase or decrease of weight, changes of the material properties or outside influences.

The used **measuring devices** (1) for a deformation monitoring depend on the **application** (2), the chosen **method** (3) and the required **regularity** (4).

Measuring devices

Measuring devices (or sensors) can be sorted in two main groups, geodetic and geotechnical sensors. Both measuring devices can be seamlessly combined in modern deformation monitoring.

- **Geodetic measuring** devices measure georeferenced displacements or movements in one, two or three dimensions. It includes the use of instruments such as total stations, levels and global navigation satellite system receivers.

- **Geotechnical measuring** devices measure non-georeferenced displacements or movements and related environmental effects or conditions. It includes the use of instruments such as extensometers, piezometers, rain gauges, thermometers, barometers, tilt meters, accelerometers, seismometers etc. Or refer to geotechnical sensors for more detail.

- **Other techniques** e.g. radar measuring devices.

Application

Deformation monitoring can be required for the following applications:

- Dams
- Roads
- Tunnels
- Bridges and Viaducts
- High-rise and historical buildings
- Foundations
- Construction sites
- Mining
- Landslide and Volcanoes Slopes
- Settlement areas
- Earthquake areas

Methods

Deformation monitoring can be made manually or automatically.

- **Manual deformation monitoring** is the operation of sensors or instruments by hand for the purpose of deformation monitoring.

- An **automatic deformation monitoring** system is a group of interacting, interrelated, or interdependent software and hardware elements forming a complex whole for deformation monitoring that, once set up, does not require human input to function.

Note that deformation analysis and interpretation of the data collected by the monitoring system is not included in this definition. An automatic monitoring system may be used for periodic or continuous monitoring.

Regularity and scheduling

The monitoring regularity and time interval of the measurements must be considered depending on the application and object to be monitored. Objects can undergo both rapid, high frequency movement and slow, gradual movement. For example, a bridge might oscillates with a period of a few seconds due to the influence of traffic and wind and also be shifting gradually due to tectonic changes.

- **Regularity**: ranges from a days, weeks or years for manual monitoring and continuous for automatic monitoring systems.

- **Measurement interval**: ranges from fractions of a second to hours.

Risk management

Deformation monitoring systems provide a proactive control of a hazard related to possible change or failure of a structure. Policyholders can reduce risk exposure before and during construction and throughout the lifecycle of the structure and hence decrease the insurance premium. Refer to Risk Management for more detail.

Automatic Deformation Monitoring System

An automatic deformation monitoring system is a group of interacting, interrelated, or interdependent software and hardware elements forming a complex whole for deformation monitoring that, once set up, does not require human input to function. Automatic deformation monitoring systems provide a critical function for the customer. In many cases an automatic deformation monitoring system saved lives and prevented the loss of millions of dollars in infrastructure and income.

Automatic deformation monitoring system components

Automatic deformation monitoring systems include:

- Consulting
- Sensors
- Communication
- Data acquisition software and data management
- Deformation analysis

Consulting

The consulting of the automatic deformation monitoring system covers a number of service activities that range from the first on site visit to sound out the situation and collect the requirements to the detailed project engineering with the selection of a suitable combination of measuring devices, mounting, power, communications, data center location and data acquisition software to the installation, operation and maintenance of the system.

Sensors

A standard geodetic monitoring instrument in the Freeport open pit mine, Indonesia

GNSS reference station antenna for structural monitoring of the Jiangying Bridge

To cover all applications an automatic deformation monitoring system must support any geodetic and geotechnical measuring device (sensor) that is required by the monitoring application.

- **Geodetic measuring** devices measure georeferenced displacements or movements in one, two or three dimensions. It includes the use of instruments such as total stations, levels and global navigation satellite system receivers.

- **Geotechnical measuring** devices measure non-georeferenced displacements or movements and related environmental effects or conditions. It includes the use of instruments such as extensometers, piezometers, rain gauges, thermometers, barometers, tilt meters, accelerometers, seismometers etc. Or refer to geotechnical sensors for more detail.

- **Other techniques** e.g. radar measuring devices.

Communication

Between measuring devices and the data acquisition software a broad range of communication alternatives are possible depending range, data rate and cost.

- Transmission cable (RS232, RS485, fiber optics)
- Local area network (LAN)
- Wireless LAN (WLAN)
- Mobile communication (GSM, GPRS, UMTS)
- WiMax

Data acquisition software including data management

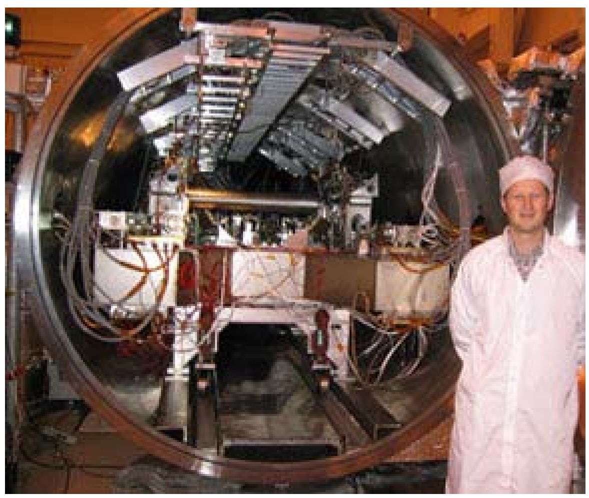
The software is the heart of the monitoring system because of its key roles in acquiring data from the attached sensors, computing meaningful values from the measurements, recording results, visualising the changes and alarming responsible persons should threshold value be exceeded. Whilst the software is the heart of the system, the operator is always the brains because they have the sufficient skills and expertise to make considered decisions on the appropriate response to the movement, e.g. independent verification though on-site inspections, re-active controls such as structural repairs and emergency responses such as shut down processes, containment processes and site evacuation.

Deformation analysis

Deformation analysis is concerned with determining of a measured displacement is statistically significant. The analysis can be done visually through the use of time line, scatter, vector and other plots and numerically. Numerical deformation analysis is directly related to the science of network adjustment.

Chapter 11

Metrology



A scientist stands in front of a microarcsecond (1 millionth of 1 arcsecond or 1 millionth of 1/3600 degree) testbed.

Metrology is the science of measurement. Metrology includes all theoretical and practical aspects of measurement. The word comes from Greek μέτρον (*metron*), "measure" + "λόγος" (*logos*), amongst others meaning "speech, oration, discourse, quote, study, calculation, reason". In Ancient Greek the term μετρολογία (*metrologia*) meant "theory of ratios".

Introduction

Metrology is defined by the *International Bureau of Weights and Measures* (BIPM) as "the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology." The *ontology* and international vocabulary of metrology (VIM) is maintained by the International Organisation for Standardisation.

Metrology is a very broad field and may be divided into three subfields:

Subfield	Definition
Scientific or fundamental metrology	concerns the establishment of *quantity systems*, unit systems, *units of measurement*, the development of new measurement methods, realisation of measurement standards and the transfer of traceability from these standards to users in society.
Applied or industrial metrology	concerns the application of measurement science to manufacturing and other processes and their use in society, ensuring the suitability of measurement instruments, their calibration and quality control of measurements.
Legal metrology	concerns regulatory requirements of measurements and measuring instruments for the protection of health, public safety, the environment, enabling taxation, protection of consumers and fair trade.

A core concept in metrology is (metrological) traceability, defined as "the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties." The level of traceability establishes the level of comparability of the measurement: whether the result of a measurement can be compared to the previous one, a measurement result a year ago, or to the result of a measurement performed anywhere else in the world.

Traceability is most often obtained by calibration, establishing the relation between the indication of a measuring instrument and the value of a measurement standard. These standards are usually coordinated by national metrological institutes: National Institute of Standards and Technology, National Physical Laboratory, UK, Physikalisch-Technische Bundesanstalt, etc.

Tracebility, accuracy, precision, systematic bias, evaluation of measurement uncertainty are critical parts of a quality management system.

Basics

Mistakes can make measurements and counts incorrect. Even if there are no mistakes, nearly all measurements are still inexact. The term 'error' is reserved for that inexactness, also called measurement uncertainty. Among the few exact measurements are:

- The absence of the quantity being measured, such as a voltmeter with its leads shorted together: the meter should read zero exactly.
- Measurement of an accepted constant under qualifying conditions, such as the triple point of pure water: the thermometer should read 273.16 kelvin (0.01 degrees Celsius, 32.018 degrees Fahrenheit) when qualified equipment is used correctly.

- Self-checking ratio metric measurements, such as a potentiometer: the ratio in between steps is independently adjusted and verified to be beyond influential inexactness.

All other measurements either have to be checked to be sufficiently correct or left to chance. Metrology is the science that establishes the correctness of specific measurement situations. This is done by anticipating and allowing for both mistakes and error. The precise distinction between measurement error and mistakes is not settled and varies by country. Repeatability and reproducibility studies help quantify the precision: one common method is an ANOVA Gauge R&R study.

Calibration is the process where metrology is applied to measurement equipment and processes to ensure conformity with a known standard of measurement, usually traceable to a national standards board.

Society

Sufficiently correct measurements are essential to commerce. About nine out of every ten people working in metrology specialize in commercial measurement, most at the technician level. Correct measurements are beneficial to manufacturing, but other methods are available and sometimes are more appropriate.

Metrology has thrived at the interface between science and manufacturing. Aerospace, commercial nuclear power, medicine, medical devices and semiconductors rely on metrology to translate theoretical science into mass produced reality.

The basic concepts of metrology appear simple on the surface, and metrology is rarely taught in a systematic manner above the technician level. Within most businesses, metrology core beliefs such as recording all setups and observations for possible future reference are opposed to the general business practice of minimizing recordkeeping to limit litigation effects.

Applied metrology

Metrology laboratories are places where both metrology and calibration work are performed. Calibration laboratories generally specialize in calibration work only.

Both metrology and calibration laboratories must isolate the work performed from influences that might affect the work. Temperature, humidity, vibration, electrical power supply, radiated energy and other influences are often controlled. Generally, it is the rate of change or instability that is more detrimental than whatever value prevails.

Calibration technicians execute calibration work. In large organizations, the work is further divided into three groups:

Group	Definition
Set-up people	arrange the equipment needed for calibration and verify that it works correctly.
Operators	execute the calibration procedures and collect data.
Tear-down people	dismantle set-ups, check the components for damage and then put the components into a stored state. This is the entry-level position for people who didn’t start in the equipment warehouse or transportation functions

Alternately, the technicians can be divided by major discipline areas: physical, dimensional, electrical, RF, microwave and so on. But the principles are the same regardless of the equipment.

Metrology technicians perform investigation work in addition to calibrations. They also apply proven principles to known situations and evaluate unexpected or contradictory results.

Specific education in metrology was formerly limited to sub-professional work. Most of the branches of the US Military train ‘enlisted-grade’ technicians to meet their specific needs.

Large industrial organizations also develop people who demonstrate aptitude in testing functions. When this is combined with an engineering degree, it qualifies the person as a metrology engineer. Over the last 15 years, Universities such as the University of North Carolina at Charlotte created a specific curriculum in metrology engineering. In England, metrology was part of the fifth year of some undergraduate engineering programmes.

Metrologists are people who perform metrology work at and above the technician levels, generally without the benefit or acknowledgement of a college degree.

The metrology and calibration work described above is always accompanied by documentation. The documentation can be divided into two types; one related to the task and the other related the administrative program. Task documentation includes calibration procedures and the data collected. Administrative program documentation includes equipment identification data, 'calibration certificates’, calibration time interval information and 'as-found' or 'out-of-tolerance' notifications.

Administrative programs provide standardization of the metrology and calibration work and make it possible to independently verify that the work was performed. Generally, the administrative program is specific to the organization performing the work and addresses customer requirements. General administrative program specifications created by industry groups, such as the ANS (ANSI) Z540 series may also be covered in the administrative program. Other specifications created by the US Food and Drug Administration, US Federal Aviation Administration or other agencies would supplement or replace ANS Z540 for work performed in their domains. Often administrative programs can be as complicated and detailed as the measurement work itself.

An administrative program that has insufficient actual metrology or calibration capability is derisively referred to as a "lick and stick" program.

Standards

Standards are objects or ideas that are designated as being authoritative for some accepted reason. Whatever value they possess is useful for comparison to unknowns for the purpose of establishing or confirming an assigned value based on the standard. The design of this comparison process for measurements is metrology. The execution of measurement comparisons for the purpose of establishing the relationship between a standard and some other measuring device is calibration.

The ideal standard is independently reproducible without uncertainty. This is what the creators of the “meter” length standard were attempting to do in the 19th century when they defined a meter as one ten-millionth of the distance from the equator to one of the Earth’s poles. Later, it was learned that the Earth’s surface is an unreliable basis for a standard. The Earth is not spherical and it is constantly changing in shape. But the special alloy meter bars that were created and accepted in that time period standardized international length measurement until the 1950s. Careful calibrations allowed tolerances as small as 10 parts per million to be distributed and reproduced in metrology laboratories worldwide, regardless of whether the rest of the metric system was implemented and in spite of the shortfalls of the meter’s original basis.

Historical International Prototype Meter bars

Modern standards

Currently, only five independent units of measure are internationally recognized: temperature interval, linear distance, electrical current, frequency and mass. All measurements of all types are based on one or more of these independent units. Two supplemental independent units are also recognized internationally, both dealing with angle measurement.

For example, Ohm's law is a widely known concept in electrical study. Of the three units of measure involved, only current (ampere) is an independent unit. Voltage and resistance units are dependent on current units, as defined by Ohm's law.

In the United States, ASTM Standard Practice E 380,replaced by IEEE/ASTM SI10 , adapts independent unit of measure theory to practical measurement activity.

It is believed that each of independent units of measure will be defined in terms of the other four independent units eventually. Length (meter) and time (second) are already connected this way. If an accurate time base is available, then a length standard can be reproduced without a meter bar artifact, using the known constant speed of light. Lesser known is the relationship between the luminance (candela) and current (ampere). The candela is defined in terms of the watt, which in turn is derived from the ampere. This difficult to recreate standard is supplemented by an incandescent bulb design that is used as a secondary and transfer standard. These bulbs recreate the candela when a specific amount of current is applied.

The development of standards follows the needs of technology. As a result, some units of measure have much more resolution than others. The second is reproducible to 1 part in 10^{14}. As it became possible to measure time more precisely, solar time, believed to be a constant, proved to be very slightly irregular. This resulted in leap second adjustments to keep UTC synchronised with solar time.

Luminance (candela) can only be reproduced to 5% of reading despite having sensors that have accuracies of +/- 50 parts per million (0.005%) precision. This is due to the standard not being accurately reproducible.

Temperature (kelvin) is defined by agreed fixed points. These points are defined by the state changes of nearly pure materials, generally as they move from liquid to solid. Between these fixed points, Standard Platinum Resistance Thermometers (SPRTs), constructed a specified manner, are used to interpolate temperature values. This mosaic of approaches produces measurement uncertainty which is not uniform over the entire range of temperature measurement. Temperature measurement is coordinated by the International Practical Temperature Scale, maintained by the BIPM.

These non-commercial measurement details used to be academic curiosities. However, engineering, manufacturing and ordinary living now routinely challenge the limits of measurement.

Industry-specific standards

In addition to standards created by national and international standards organizations, many large and small industrial companies also define metrology standards and procedures to meet their particular needs for technically and economically competitive manufacturing. These standards and procedures, while drawing in part upon the national and international standards, also address the issues of what specific instrument technology will be used to measure each quantity, how often each quantity will be measured, and which definition of each quantity will be used as the basis for accomplishing the process control that their manufacturing and product specifications require. Industrial metrology standards include dynamic control plans, also known as “dimensional control plans”, or “DCPs”, for their products.

In industrial metrology, several issues beyond accuracy constrain the usability of metrology methods. These include

- The speed with which measurements can be accomplished on parts or surfaces in the process of manufacturing, which must match the TAKT Time of the production line.
- The completeness with which the manufactured part can be measured such as described in high-definition metrology,
- The ability of the measurement mechanism to operate reliably in a manufacturing plant environment considering temperature, vibration, dust, and a host of other potential hostile factors,
- The ability of the measurement results, as they are presented, to be assimilated by the manufacturing operators or automation in time to effectively control the manufacturing process variables, and
- The total financial cost of measuring each part.

National standards

Every country maintains its own metrology system. In the United States, the National Institute of Standards and Technology (NIST) plays the dual role of maintaining and furthering both commercial and scientific metrology. NIST does not enforce measurement accuracy directly.

The accuracy and traceability of commercial measurements is enforced per the laws of the individual states. Commercial measurement generally involves any material sold by any unit of measure. Some intuitive or obvious measurement is generally exempted, such as selling cloth on a cutting table that has a yardstick fastened to it. All counting-based transactions are generally exempt also. But each state has its own rules, responding to the accumulated concerns of the state residents.

Commercial metrology is also known as "weights and measures" and is essential to commerce of any kind above the pure barter level. Every state maintains its own weights and measures functionality with traceability to the national standards maintained by NIST. Large states further divide this effort by county, where a "Sealer" or other appointee is responsible for the validity of most common commercial measurements such as mass balances (scales) in grocery stores and gasoline pump measurements of volume. The sealer's staff and agents make periodic inspections to catch merchant cheaters, maintaining the integrity of commercial measurements.

Typical State Seal application.

Depending on the specific state, other state government agencies can be involved. For example, electricity watt-hour meters and water delivery flow meters are commonly monitored by the state's "public utilities commission" who enforces the measurement tolerances and traceability to NIST through the utility providers. Highway State Police and the State Highway Department generally run the commercial truck weight measurement programs for safety purposes and to minimize the damage to road surfaces that overloaded trucks cause. Nearly all states license weighmasters, weighmistresses, scale calibrators and other specialists involved in commercial measuring equipment maintenance.

The term "commercial metrology" is also used to describe calibration laboratories that are not owned by the companies they serve.

Scientific metrology addresses measurement phenomena not quantified in ordinary commerce, such as the test bed pictured at the beginning. Calibration laboratories that serve scientific metrology are regulated as businesses only. They may choose to have their work accredited by voluntary certification organizations based on customer desires, but there is no requirement to do so. Irresolvable disputes involving scientific metrology are generally settled in the civil court systems. Some federal government entities like the Federal Communications Commission and the Environmental Protection Administration are considered to be the final authority in their domains rather than the NIST. Disputes involving only metrology issues with those organizations probably would not be heard in any courts.

Historical development

Metrology has existed in some form or another since antiquity. The earliest forms of metrology were simply arbitrary standards set up by regional or local authorities, often based on practical measures such as the length of an arm. The earliest examples of these standardized measures are length, time, and weight. These standards were established in order to facilitate commerce and record human activity.

Little progress was made with regard to proto-metrology until various scientists, chemists, and physicists started making headway during the scientific revolution. With the advances in the sciences, the comparison of experiment to theory required a rational system of units, and something more closely resembling modern metrology began to come into being. The discovery of atoms, electricity, thermodynamics, and other fundamental scientific principles could be applied to standards of measurement, and many inventions made it easier to quantitatively or qualitatively assess physical properties, using the defined units of measurement established by science.

Metrology was thus one of the precursors to the Industrial Revolution, and was necessary for the implementation of mass production, equipment commonality, and assembly lines.

Modern metrology has its roots in the French Revolution, with the political motivation to harmonize units all over France and the concept of establishing units of measurement based on constants of nature, and thus making measurement units available "for all people, for all time". In this case deriving a unit of length from the dimensions of the Earth, and a unit of mass from a cube of water. The result was platinum standards for the meter and the kilogram established as the basis of the metric system on June 22, 1799. This further led to the creation of the Système International d'Unités, or the International System of Units. This system has gained unprecedented worldwide acceptance as definitions and standards of modern measurement units. Though not the official system of units of all nations, the definitions and specifications of SI are globally accepted and recognized. The SI is maintained under the auspices of the Metre Convention and its institutions, the General Conference on Weights and Measures, or CGPM, its executive branch the International Committee for Weights and Measures, or CIPM, and its technical institution the International Bureau of Weights and Measures, or BIPM.

As the authorities on SI, these organizations establish and promulgate the SI, with the ambition to be able to service all. This includes introducing new units, such as the relatively new unit, the mole, to encompass metrology in chemistry. These units are then established and maintained through various agencies in each country, and establish a hierarchy of measurement standards that can be traced back to the established standard unit, a concept known as metrological traceability. The U.S. agencies holding this responsibility are the National Institute of Standards and Technology (NIST) and the American National Standards Institute (ANSI).

The development of standards also does involve individual and small group achievements. In 1893, Edward Weston (chemist) and his company perfected his Saturated Standard Cell design, which allowed the volt to be reproduced to 1 part in ten to the fourth power directly. This advance made a huge practical difference at a critical moment in the development of modern electrical devices. Groupings of saturated cells, called banks, can still be found in some metrology and calibration laboratories today. Edward Weston did not pursue patents for his cell design. By doing this, his superior design quickly replaced similar but inferior patented devices worldwide without much discussion.

Mechanisms

At the base of metrology is the definition, realisation and dissemination of units of measurement. Physical or chemical properties are quantised by assigning a property value in some multiple of a measurement unit.

The basic 'lineage' of measurement standards are:

- The definition of a unit, based on some physical constant, such as absolute zero, the freezing point of water, etc.; or an agreed-upon arbitrary standard.
- The realisation of the unit by experimental methods and the scaling into multiples and submultiples, by establishment of primary standards. In some cases an approximation is used, when the realisation of the units is less precise than other methods of generating a scale of the quantity in question. This is presently the situation for the electrical units in the SI, where voltage and resistance are defined in terms of the ampere, but are used in practice from realisations based on the Josephson effect and the quantised Hall effect.
- the transfer of traceability from the primary standards to secondary and working standards. This is achieved by calibration.

Theoretically, metrology, as the science of measurement, attempts to validate the data obtained from test equipment. Though metrology is the science of measurement, in practical applications, it is the enforcement, verification and validation of predefined standards for:

Criterion	Definition
Accuracy	is the degree of exactness which the final product corresponds to the measurement standard.
Precision	refers to the ability of a measurement to be consistently reproduced.
Reliability	refers to the consistency of accurate results over consecutive measurements over time.
Traceability	refers to the ongoing validations that the measurement of the final product conforms to the original standard of measurement.

These standards can vary widely, but are often mandated by governments, agencies, and treaties such as the International Organization for Standardization, the Metre Convention, or the FDA. These agencies promulgate policies and regulations that standardize industries, countries, and streamline international trade, products, and measurements. Metrology is, at its core, an analysis of the uncertainty of individual measurements, and attempts to validate each measurement made with a given instrument, and the data obtained from it. The dissemination of traceability to consumers in society is often performed by a dedicated calibration laboratory with a recognized quality system in compliance with such standards. National laboratory accreditation schemes have been established to offer third-party assessment of such quality systems. A central requirement of these accreditations is documented traceability to national or international standards.

Some common standards include:

- ISO 17025:2005—General Requirements for Calibration Laboratories
- ISO 9000—Quality Systems Management
- ISO 14000—Environmental Management
- 21 CFR Part 210/211—FDA Regulations concerning GMP (Good Manufacturing Practices) Quality Systems
- 21 CFR Part 110—FDA Regulations concerning Food Industry GMP's.

Time and frequency metrology

This area of metrology studies components and their characteristics, especially

- frequency standards
- synthesizers
- oscillators
- digital clocks