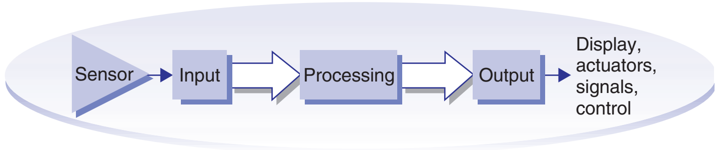

Why Do We Care About Measurement?

The first in a series of tutorials in instrumentation and measurement.

Kim R. Fowler and John Schmalzel

The I&M Tutorial Series

The IEEE Instrumentation and Measurement (I&M) Society surveyed its membership during the summer of 2003 to clarify *IEEE Instrumentation and Measurement Magazine's* role and purpose. One prominent result was the need for tutorials on I&M. The response to our survey heavily favored a regular feature in the magazine.

So here we are, beginning a regular tutorial that will appear in each issue of the magazine. We will ask people with specific I&M expertise to write articles. Each article will focus on a different concern. Its purpose is to help folks at all levels. Some might be just getting into the discipline and wanting to learn the basics of I&M, general definitions, and common concerns. Moreover, these general areas of knowledge need to be made useful by tying together various I&M elements. Others already working in the field may want introductions to, and possibly more depth in, new and emerging areas.

All of the articles will be written at a level of a basic undergraduate textbook. To make them as useful as possible, we need your input. That is, we need to know how well the articles meet your needs. Are they clear? Are they useful? Do they provide the background you need? What topics would you like to see? So, please e-mail or call us with your ideas.

You will note that the little diagram, at the top of the title page and each of the odd-numbered pages within this tutorial, repeats this basic outline for a measurement system. For each article, we will put this little diagram at the top of selected pages to reinforce the tutorial nature of the article. We will also shade the portion of the measurement system in the diagram that the article covers.

We have a colloquial expression in America, "Don't miss the forest for the trees." It means that by focusing on the details we tend to overlook the big picture, which is something that we do sometimes—see the details but miss the overall perspective. These tutorials aim to overcome this myopic view of development and to provide you with a bigger picture—or the systems perspective. Our hope is that understanding the system will thereby help you build more useful instruments.

This first tutorial is introductory and provides a basic systems overview.

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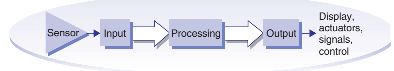


Why is measurement important? Beyond supplying vocational and professional needs, why does measurement merit further examination? Ando Linklater, in his fine book, *Measuring America*, gives a clear answer to the question: "Measurement . . . is so universal as not to merit a second thought. Yet without it, the exchange of goods and services cannot take place. Measuring a length of cloth or a herd of animals or a day's labor gives it a value in terms of size, or number, or achievement, which enables others in the community to offer something else—food, protection, even love or loyalty—of equivalent value. Consequently, it is almost as necessary to human society as language, and it occurs in the earliest civilizations, long before the development of writing." Linklater goes on to say, "Without the conscious decision to agree on a way of measuring, cooperative activity could hardly take place. With it, marketplaces and increasingly sophisticated economies can develop, matching barter, cash, or credit to whatever is owned by one person and desired by another." [1]

Why Measure Anything?

If you cannot measure it, you cannot control it.
If you cannot control it, you cannot manage it.
If you cannot manage it, you cannot improve it.
(Paraphrased from Dr. H. James Harrington, 1991)

Measurement goes beyond geopolitical economics. Measurement provides definition and helps us understand quality and consistency; two example areas are medicine and production (replication). Quality of life is important to most of us; consequently, medicine is important to us. We need to define what we mean when we say "quality of life," and then physicians need to be able to measure it as they treat patients. We can't replicate quality if we can't measure it first. Clearly, manufacturing requires measurement to replicate merchandise and then control its production. Teaching, which we hope is not treated like an assembly line, still requires someone to effectively replicate their expertise by transfering it to students in quantifiable units. An artist training an apprentice must be able to describe color, lighting, shading, texture, dimensionality, proportion, and perspective—this is replication of expertise in quantifiable and understandable terms.

Measurement also helps us express appreciation; two examples are sports and art. How else can you succinctly describe a 98-mph fastball without a radar gun and a general understanding of speed? If video systems and photoelectric sensors did not exist, we couldn't always settle a horse race or a NASCAR event without degenerating into tribal warfare. Appreciating a fine piece of art or music may be primarily qualitative; however, we can often use meaningful quantifiable and understandable units—its size or proportion or rhythm or color. These are all things that we can appreciate, because we have some way to measure them.

So, we leave as fact that measurement is integral to life. It follows then that if we need measurement then we need instrumentation to perform those measurements. Further, if we need sophisticated measurements, then we generally need sophisticated instruments. This series of tutorials will provide a basis for understanding the instrumentation that you can fit to your particular measurement application.

A Little History

Any time a new phenomenon occurs, mankind sets about to understand it. First, we recognize it as a phenomenon. Then we try to describe it qualitatively. After some familiarity, we begin measuring it quantitatively. With time, we refine our measurements and set standards. Finally, we incorporate the new measurements into regular processes that we use to advance our capabilities.

Common examples abound. A widely repeated urban legend is that the track spacing of today's standard railroad gauge (4 ft. 8 1/2 in. or 1,435 mm) is ultimately derived from the wheel spacing of Roman chariots. The measurement of time followed a similar trajectory of technology. Recognized as critical to advances in seafaring, Britain's Parliament offered prize money for just such advanced time-keeping instruments, which provided accurate timekeeping over extended periods of time and in all manners of environmental extremes. Closely associated was the recognition that accuracy allowed comparison. In turn, that underscored the need for a standard, which is a component to the genesis of the several international standards bodies that exist today.

Basic Instrumentation

With that background, let's now look at the basic outline for instrumentation. Figure 1 illustrates the general stages of measurement and their functions and operations. Each of these stages participates in obtaining information from an event.

The sensors detect the physical event and make the original transformation of data from one domain to another, thereby relating the two domains. (In most cases, sensors transduce or transform a physical quantity into an electrical signal. These are the types of sensors that we will focus some of our tutorial discussions.) Furthermore, the relationship

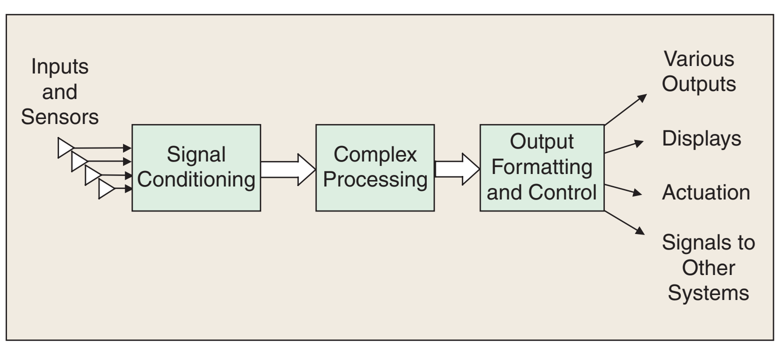


Fig. 1. Basic outline of a measurement system (from [3]).

between the domains must be based on a reference, which requires systematic calibration.

The following stages condition and process the signals that represent the original data. They may also fuse, combine, or reduce the data.

The final stage performs conversion of data into signals that drive outputs and displays. This is the final representation of the measurement.

"Measurement . . . is so universal as not to merit a second thought. Yet without it, the exchange of goods and services cannot take place."

Measurements Must Have a Reference

Measurement must have meaning. It represents a substantive result with which the person who performs the measure can relate.

Measurement provides a relationship between one domain and another. Measurement in isolation is meaningless. It must fit into the understanding of a system, which has relational, interacting components. Measurement always has a reference basis from which it establishes a relationship between the domains. For example, the common thermocouple measurement produces a voltage proportional to the temperature of the junction; however, it bases its reference to a standard junction operating at the ice-point of water (0° C).

We have already introduced how we measure. Now you need to understand who uses measurement and where we perform measurements. Then you can use basic principles from engineering and science and principles of human interactions to construct better, more-useful instruments. The principles of human interaction have many names: ergonomics, user interfacing, interaction design, or human factors; sometimes you might just see them as common sense.

People

People who need a greater understanding of measurement fall into four groups: 1) users, 2) originators of the need for measurement, 3) owners of the equipment, and 4) designers of the equipment. These people may also be considered customers; we have discriminated among them to illustrate the wide variety of people that your system must satisfy.

Users are those who perform the measurement. They may be scientists conducting precise and accurate laboratory experiments. They may be engineers extracting samples from the field. Users could also be process technicians working in a refinery, or they may be an operator reading the battery-charge gauge on the dashboard of a forklift. Regardless, they are the end users of the information acquired from the measurement.

Sometimes, the originators of the need for measurement are also users. Frequently, the originator is management requesting information about operations.

After the originators are the equipment owners, another important group. They need to keep their measurement equipment in proper condition, relying on calibration, training, etc. to ensure maximum return on investment.

Finally, equipment designers use measurements extensively to judge performance of the equipment and systems that they build.

Where Do We Use Measurements?

We measure to reveal a condition and possibly alert the user. We also measure to quantify the magnitude of phenomena. Probably most importantly, we measure to control processes. All these should lead to insight to phenomena and processes. Ultimately it provides an interpretation of events.

Basic Principles

The most important part of giving meaning to measurement is to provide understanding into the measurement process. This understanding should extend throughout the entire process, including the physical phenomena involved, the actual measurement sampling and transformation, data manipulation, and the end result or actuation.

The components of understanding include:

- visibility
- simplicity and clarity
- hidden complexity
- tailoring to the audience
- traceability to a reference.

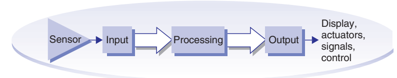
Visibility

First, you should provide visibility into the basic process. The temperature gauge on an automobile's instrument panel is an example. It clues the driver in on an important parameter of engine operation; if the indicator temperature is higher than normal, that condition should alert the driver to a malfunction of the engine, particularly its cooling system. This is a simple measurement system. The transformation relates temperature into a visual indication. Little actual data processing is carried out by the measurement system; the driver performs further interpretation of the data.

Another example of providing visibility into the basic process is the saving of files in software indicated by a sliding bar to indicate how much has been done. It quantifies the amount of data to be stored and how much has already been stored. The transformation maps the quantity of binary bits into a visual indication. The process does some data processing so that the user receives a recognizable interpretation of the data.

Simplicity, Clarity, and Complexity Hiding

Second, you should simplify and clarify the measurement process, thereby hiding complexity. The temperature gauge in an automobile is simple but it hides some complex functions such as combustion of the fuel, the pumping of coolant,



and heat transfer through the radiator. The bar indicator for saving data summarizes the overall operation and hides the complexity of digital signals, data bus addressing, moving data from memory to a disk drive, and encoding the binary bits into magnetic domains on the disk.

Tailoring to the Audience

Next, you should tailor the measurement process to the audience of users. You need to know what kind of information the user wants. You need to know the user's capability, experience, and knowledge. You also need to know what the user is doing. Understanding the user will help you provide the appropriate information about the measurement process.

Most drivers reading an automobile's temperature gauge want only to know the general range of temperature. If the temperature exceeds an acceptable range, then they take the car in for repair. An engineer developing engine controls will want far more precise temperature readings to tune the engine control for efficiency.

Traceability to a Reference

Finally, you should make the measurement process traceable to a reference. The measurement becomes meaningless if there is no basis for its reference. An uncalibrated sensor and measurement system does not provide the user with accurate feedback, insight, or control. The sensor for the automotive temperature gauge needs an initial calibration to prove that it is accurate for the range of temperatures that it measures.

A group of scientists and engineers had an experiment fail because the sensors and measurement system lacked calibration. They had set out to measure the temperature of seawater around the hull of a submarine. The data-acquisition system used thermocouples sampled by 16-b analog-to-digital converters. Unfortunately, no one had thought to calibrate the sensors or the system, so they collected volumes of high-resolution, meaningless data.

Pertinent Issues

Each subsystem within a measuring instrument has special concerns. The sensors must reliably and accurately represent the phenomenon. Insofar as possible, it should be very specific to the intended signal and not be influenced by other parameters. You'd like your sensor to be unaffected by temperature—unless you're measuring temperature, for example! Transducers are the first location of data transformation, typically from the physical domain into the data domain.

Often, the output from sensors is not immediately usable. A sensor's signals may be conditioned to present data values that are easily used and understood. Filtering high-frequency noise or performing linear curve fitting are examples of conditioning.

Measurement is integral to life. It follows then that if we need measurement then we need instrumentation to perform those measurements.

The processing section must make sense of the data from the sensors. Processing can be very complex in some instruments such as the backprojection algorithms needed to process data from arrays of imaging sensors.

The actuation subsystem has concerns similar to those for the sensors. For example, a complex control loop is required to continuously steer and focus the laser beam assembly used for reading from and writing to compact disks.

Finally, the output may feed back to the input sensors to complete a control loop (nested loops may reside within the processing subsystem also).

Case Studies

We will illustrate how meaning may be given to measurement through four case studies. Each case study will illustrate the measurement process as diagramed above and then describe how the basic principles of understanding apply to give meaning to the process.

Case Study 1: Automobile Engine Control

THE PROBLEM

An engine control has several, simultaneous objectives. It must balance power, efficiency, and emissions within the internal combustion engine of an automobile. This is a significant problem.

THE SITUATION

The engine control operates in a harsh environment and must make high-speed, real-time adjustments to the engine. Measurements and adjustments must occur within milliseconds to control the engine properly. Temperatures within the engine compartment may range from below freezing in winter to above boiling in the summer. Moisture and corrosive fluids can attack cabling, hoses, belts, electronic components, and electrical connections.

MEASUREMENT

The engine control has multiple inputs. Some parameters that may be sampled include coolant temperature, barometric pressure, oxygen in the exhaust, knock (or pre-ignition detonation), engine rpm, and throttle setting. Each of these inputs has its own sensor that requires its own reference and calibration.

PROCESSING

The raw outputs of these sensors are fairly meaningless without signal conditioning, data reduction, and data fusion. The engine control module (ECM), or some people call it the electronic control module, takes in these sensor signals and performs the necessary data processing. An ECM uses complex calculations and large lookup tables to process the data.

OUTPUT

The ECM then converts the data into usable actuation signals to control the fuel flow and mixture, the ignition timing, and the radiator's electric fan. The result is a smooth power curve from the engine that balances efficiency and emissions.

DISPLAY

There is no explicit indication of the engine's performance other than the tachometer and speedometer, each of which displays only a single parameter. The primary output is the inertial sense of acceleration. This is the only form of visibility that the user has into the process of engine control; it is simple and clear and thus most appropriate, as well.

Real-time updates of the physical parameters are meaningless to an automobile driver; hence, hiding those parameters hides complexity and simplifies and clarifies the information load on the driver. The ECM provides understanding and feedback, which is a form of visibility, by being responsive to the expectations of the driver.

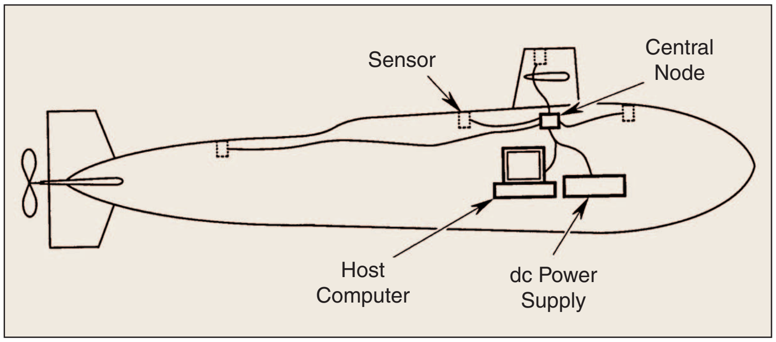


Fig. 2. Data acquisition system for detecting laser pulses at the hull of a submarine. (© 1996, Oxford University Press, Inc. Used with permission.)

Case Study 2: Submarine Data-Acquisition System

THE PROBLEM

Kim worked on a project years ago that studied light propagation through water. The Navy sponsor needed a sophisticated data-acquisition system that could detect laser pulses and measure their intensity at the hull of a submerged submarine. See Figure 2.

THE SITUATION

The system needed to survive the crushing depths of the ocean and collect data from

Fig. 3. Sensors under test in an environmental chamber. (Photograph courtesy of the Johns Hopkins University Applied Physics Laboratory.)

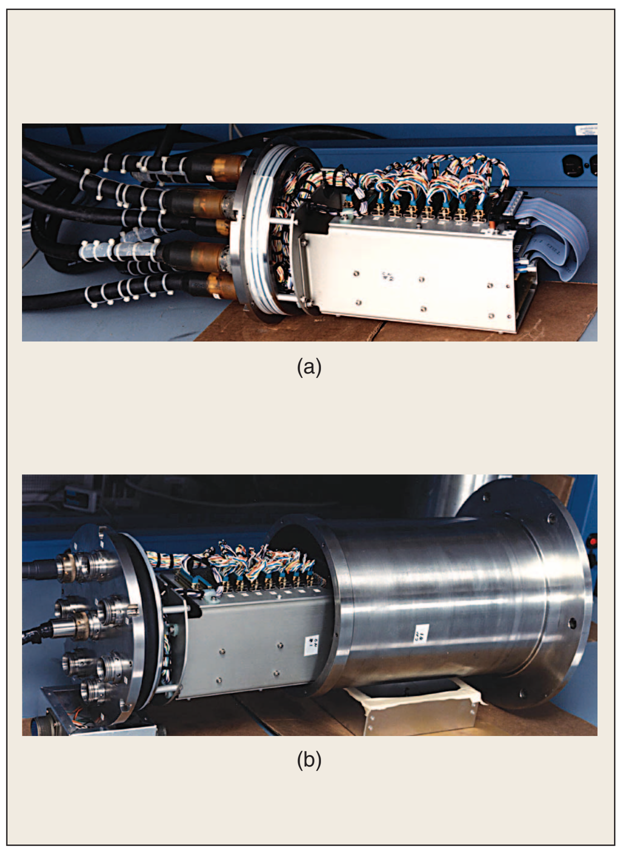


Fig. 4. Central node that collected data from the sensors and transmitted the data to the computer. (Photograph courtesy of the Johns Hopkins University Applied Physics Laboratory.)

distant points on the hull. Sensors had to collect detections, digitize the data, and transmit the data, through a central node that concentrated the data, to a central computer for display and processing. Figures 3 and 4 are photographs of both the sensors under test and the central node. The sponsor also mandated low-voltage, 36 VDC power distributed to the sensors.

MEASUREMENT

The measurements needed to occur within tens of microseconds and be accurate to about 14 effective number of bits (ENOB). A photodetector captured the light pulses; analog conditioning circuitry then stored the charge representing the intensity of the light while a 16-b converter translated the intensity into the digital domain. Figure 5 is a sensor with its stainless-steel enclosure removed. The sensors transmitted the data in differential, digital format to the central node and then to the processing computer.

PROCESSING

The processing occurred in two stages. First, the sensors performed the analog-to-digital conversion, then a computer further filtered and converted the formats into easily displayed and stored values. Figure 6 shows the computer strapped into its workspace on the submarine.

OUTPUT AND DISPLAY

The output was displayed on the monitor of the computer or printed on paper. Since this was a scientific investigation, no further control actions were contemplated.

GIVING MEANING TO MEASUREMENT

This case study has all the basic principles of giving meaning to measurement. It demonstrates visibility, hiding complexity, simplicity, tailoring to the users, and traceability to a reference.

The system hides the complexity of all the details in sensing and transmitting the detected pulses, while making it readily apparent to the operator that detections have occurred. It simplifies consolidating the measurements into a single screen on the computer that indicates which sensors detect pulses. At the same time, it collects all the parameters of the measurements—pulse intensity, time of arrival, and sensor number. This tailors data to the users: scientists and engineers who want to see and understand the data. Finally, the submarine passed its timebase to the computer as a reference for the time and background lighting is the reference for pulse intensity. The reference traceability is both an accepted timebase and a relative comparison between the ambient background lighting and the intensity of the actual pulses.

Case Study 3: LOX Tank Level

THE PROBLEM

The testing of rocket engines requires that a run tank be filled with liquid oxygen (LOX) to a specified level to provide the correct amount for a given test. Underfilling can result in an incomplete test; overfilling involves unrecoverable costs. Measurement of the content volume within the tank is therefore of great interest.

THE SITUATION

Liquid oxygen is a cryogen (–183 °C), which means that any sort of level sensor must work reliably in very cold environments. Because it is such a good oxidizer, many precautions must be taken to avoid introducing some sort of spark or other localized thermal event that could start a fire. (Yes, stainless steel will burn!)

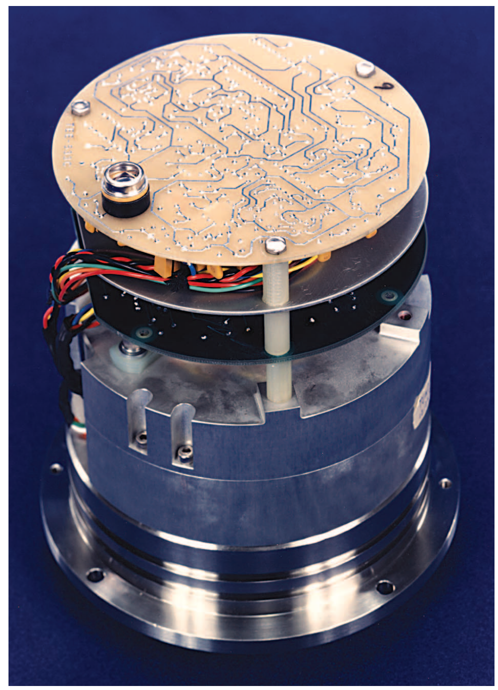
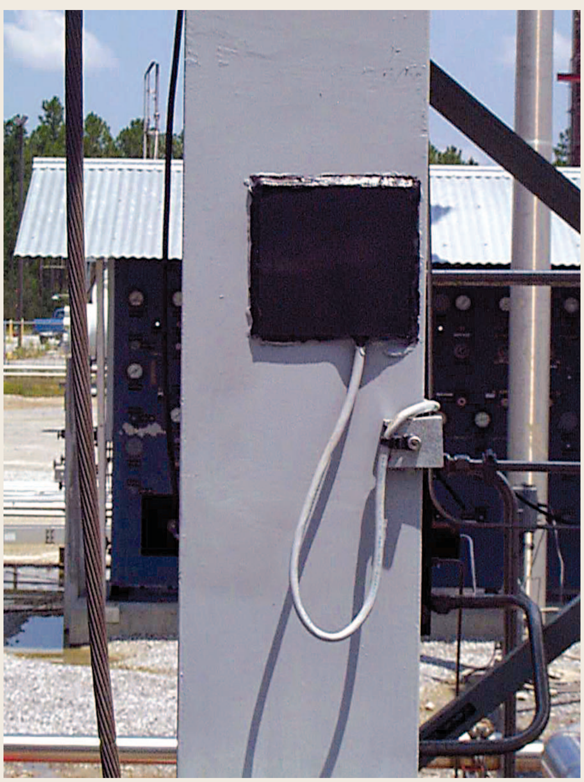


Fig. 5. Sensor with its stainless steel enclosure removed. (Photograph courtesy of the Johns Hopkins University Applied Physics Laboratory.)

Fig. 6. Computer, power supply, and printer strapped down within the submarine. (Photograph courtesy of the Johns Hopkins University Applied Physics Laboratory.)

(a)



(b)

Fig. 7. LOX tank for rocket engine testing and its strain gauge for sensing volume. (Photograph courtesy of NASA-Stennis Space Center.)

MEASUREMENT

Several techniques may be applied to determine the level in the tank. It could be directly sensed using some sort of float or some other determination of fluid height. Alternatively, an indirect technique could be used that involves measuring stress on selected tank components to infer the mass of LOX in the tank. See Figure 7.

PROCESSING

In a recent approach, the level in an LOX tank was measured using fiber-optic strain sensors [2]. The measurement principles involve detection and processing of optical interference patterns created by displacement of one end of a Bragg cell. See Figure 8.

OUTPUT

The fiber-optic sensor returns strain as a function of change of mass within the tank. Calibration of the sensor output with known mass changes can provide high confidence in the derived LOX volumes.

DISPLAY

The results of level determination are made available to associated control systems as well as being included as part of the operator's display consoles. Tank levels can be displayed as both numeric values as well as graphically using a graphical object in software for the tank display.

GIVING MEANING TO MEASUREMENT

This case study has all the basic principles of giving meaning to measurement. It demonstrates visibility, complexity hiding, simplicity, tailoring to the users, and traceability to a reference.

The system hides the complexity of all the details in sensing and transmitting the detected LOX level. It transforms a strain measurement into a representation of volume. It makes the measurement visible by making it readily apparent to the operator what the LOX level is. It simplifies the act of measuring and allows the operator (user) to choose between numeric and graphic display. This tailors data for the users who operate the LOX tank and perform the rocket-engine test. The reference traceability is the calibration of the strain sensor on the leg of the LOX tank.

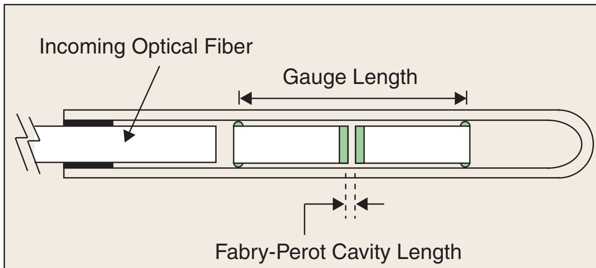


Fig. 8. Diagram of the fiber optic strain gauge, a Fabry-Perot FOSG: Schematic (Courtesy of FISO Technologies, Inc. Sainte-Foy (Quebec), Canada G1N-4N6.)

Case Study 4: Chronic Pain

THE PROBLEM AND TREATMENT

Okay, some of you have seen this case study before. It is worthwhile repeating because it is another example of how measurement systems are a part of everyday life.

The most important part of giving meaning to measurement is to provide understanding into the measurement process.

Accidents, advancing disease, or multiple failed back surgeries leave some people suffering pain in their back and legs. Sometimes physical therapy, drugs, and additional surgery do not relieve the pain. When relief does not occur, these patients are chronically debilitated. They can't work. They develop psychological problems. Their families suffer as well, and form dysfunctional relationships similar to those dealing with an alcoholic family member.

For patients desiring to return to work and reduce their dependence on others, stimulation of the spinal cord can provide relief from the pain. Sometimes stimulation can eliminate the pain completely.

An implanted electrical device provides the stimulation by driving minute currents through nerves in the spine to block signals that represent pain (Figure 9). The stimulation evokes a sensation, called paresthesia, while at the same time producing relief from pain, called analgesia. To reduce pain (i.e., to produce analgesia), the paresthesia should overlap the area of pain.

Historically, the first stimulation devices available in the 1960s and 1970s were single-channel systems that drove monopolar or fixed bipolar electrodes. The position of the electrodes near the spinal cord was critical for relief from pain. The 1980s saw the development of programmable, multicontact systems that allowed "fine tuning" of the location of the stimulus to improve the management of pain.

THE SITUATION

Stimulation systems have up to 16 electrodes. These systems require the adjustment of multiple parameters such as pulse width, frequency, and stimulus amplitude, which gives rise to a factorial increase in the number of possible settings. Until recently, the physician practitioner manually adjusted these pulse parameters. Yet, the adjustment poses considerable challenge. The number of possible polarity assignments expands enormously with the number of electrodes. There are 50 possible polarity assignments for an array of four electrodes, 6,050 polarity assignments for an array of eight electrodes, and about 50 million for an array of 16. Clearly, more electrodes tax the capability of the practitioner to optimize treatment to relieve pain. Compounding the problem even further are adjustments to the stimulation's pulse width or frequency.

A Patient-Interactive Programmer

These challenges have been met by the development of a patient-interactive programmer that incorporates a pentop computer for use by patients (Figure 10). The programmer presents the available electrode combinations and stimulus parameters at a much higher rate than a practitioner

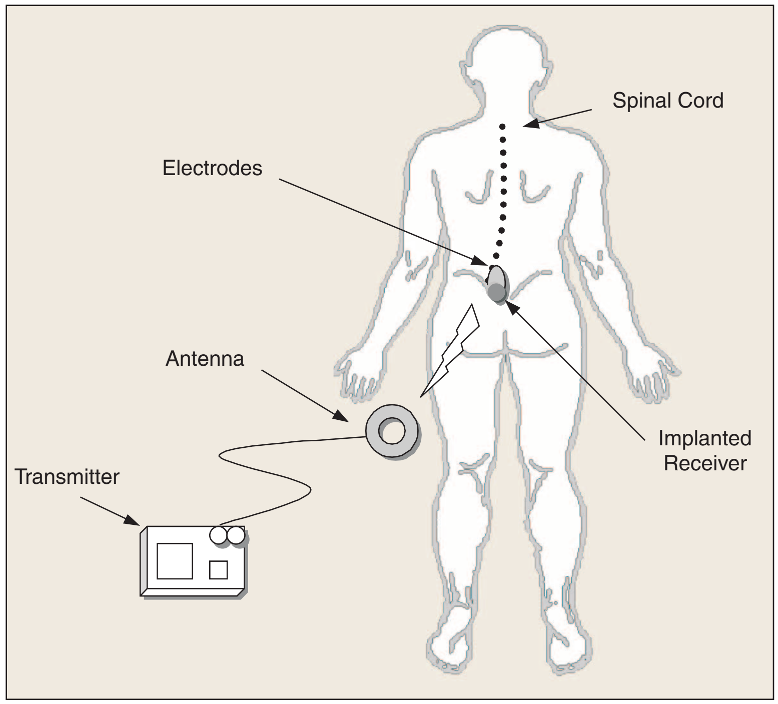


Fig. 9. Stimulation to relieve chronic pain.

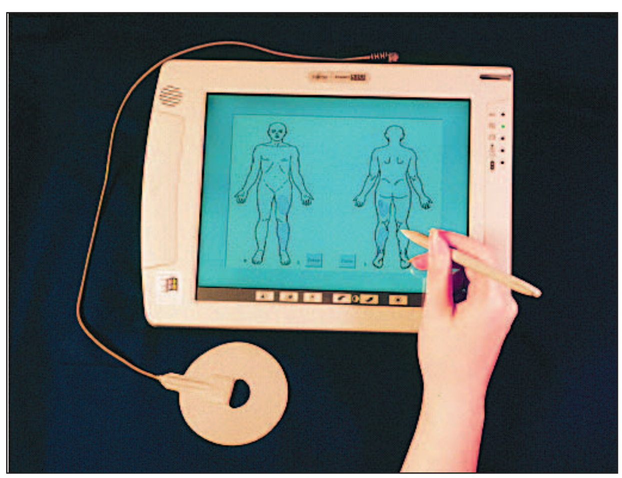


Fig. 10. Pentop computer that adjusts stimulation treatment and used by patient to draw responses (from [3]).

This tutorial series in *IEEE I&M Magazine* aims at helping you build effective measurement systems. We will cover many basic issues to help you better understand each component of a measurement system. We will strive to instruct a systems perspective to designing and developing instruments. Again, we need your input. Please e-mail or call us with your ideas.

can by manual operation. Moreover, it gives control to the patient, who can adjust these parameters without supervision from a physician.

MEASUREMENT

The programmer allows patients to use drawings and simple controls to describe pain and paresthesia. The measurements are drawings of pain or paresthesia on body outlines, rating marks, and controls made by the patient and displayed on the screen.

These measurements are easy for patients to make and understand. Consequently, these measurements provide visibility into the process and give patients some control over their treatment. Patient involvement in treatment is known to improve medical outcomes.

PROCESSING

The programmer calculates overlap of pain by the stimulation paresthesias. It is the intersection of the areas of pain and paresthesia versus the union of those same areas.

OUTPUT

The programmer provides as output both the percent overlap and the subjective scores from the patient.

DISPLAY

The programmer can provide these outputs as either drawings or values in a spreadsheet table. The drawings, showing the overlap of pain by stimulation paresthesia, are more immediately intuitive. The table, displaying percent overlap as a number, is more precise and accurate.

This case study is an example where understanding the users is important to provide an appropriate output and display. Clinicians new to the programmer tend to review drawings because the results are more immediately intuitive. Experienced physicians already understand the basic model of overlap and tend to use the table with numbers, which represent percent overlap, because it is faster to read.

GIVING MEANING TO MEASUREMENT

This case study represents several basic principles of giving meaning to measurement. It shows the importance of complexity hiding, simplicity, and tailoring to the audience of users.

The patient-interactive programmer hides the complexity of myriad mundane details. It also simplifies the entire process. Finally, it tailors its operations to the users, both patients and physicians. Patients, who may be illiterate, use simple drawings and buttons. Physicians, who need volumes of precise data, can review the data in tables or through drawings.

Closing Thoughts

As scientists and engineers, we typically understand the physical principles behind measurement. Unfortunately, we do not always convey the meaning of the measurement to the end-user. There is hope, though. Know the users. Provide them with understanding of the process. Clarify, simplify, and hide complexity.

We need to gain an overall, systems perspective to measurement. The right perspective will help us avoid "missing the forest for the trees."

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