Abstract

A novel feature of our engineering physics program is a 2-credit laboratory course covering sensors and sensor systems. The engineering physics program accentuates areas which are multidisciplinary with an engineering curriculum emphasizing physics, electrical, and mechanical engineering. Following the advice of our industrial advisors, we have developed a course which covers basic sensor technologies, sensor calibration and applications, as well as signal conditioning and computer interfacing. This paper discusses the different types of sensors and the experiments which were developed to study them.

1. Introduction

The Engineering Physics (EP) program at the University of Wisconsin - Platteville began in the Fall of 1996. The EP program was born out of a traditional physics program. Little of the physics curriculum was completely removed in this transformation, although a small number of credits were taken from existing upper level physics courses and replaced with novel EP courses. Three such courses were developed, the engineering physics laboratory (formally advanced physics laboratory), sensors laboratory (formally two credits of advanced modern physics), and senior design (a new capstone course). It is the sensors laboratory course which is the substance of this paper.

The motivation for a laboratory course in sensors originally derived from consultation with our industrial partners and advisors selected to help with the development of the EP curriculum. It was suggested that having some kind of area of specialization would be beneficial and that sensors was an imported area to much of industry and yet not emphasized in any engineering curriculum. From the beginning, the EP program set out to form a multi-disciplinary engineering degree with its upper level engineering curriculum deriving from a mixture of physics, electrical, and mechanical engineering. Thus a subsequent motivation for this course was to have a laboratory course where students work with multi-disciplinary systems. Specifically, the program wanted to create a course which offered a novel area of specialization, multi-disciplinary systems, sensors, and design. As a result, a laboratory course in sensors has been developed which covers the physics exploited in a variety of sensors, basic signal conditioning electronics, computer interfacing, sensor calibration, computer control of...
some form of mechanical motion device, and design of an electromechanical system incorporating sensors for feedback.

2. Sensors and Sensor Systems

Sensors may be defined by the purpose they serve, to translate some physical occurrence into an electrical signal. This is distinguished from a transducer, a device which converts one form of energy into another, not necessarily electrical. The sensor may or may not incorporate a transducer. Sensors range in principle from the very simple to extremely sophisticated. For example, a tilt sensor may be constructed in the form of a switch utilizing a metal ball on rails which depending on inclination either completes or opens an electric circuit. At the other end of the technological spectrum are 3D magnetoresistive integrated circuits and micro-machined spring-mass-damper accelerometers. Sensors are used to measure both the external environment, such as a room’s humidity, or the environment internal to the device, such as the temperature of a p-n junction. Sensors may be passive or active. A strain gauge is a passive device in that it does not produce usable energy but merely responds to strain by a change in its electrical resistance. A simple active sensor is a coil. A magnetic object passing through its windings produces a usable current. Sensors are always a part of a larger system. Figure 2.1 illustrates the place of the sensor in a typical open-loop sensor system. This is not an all encompassing block diagram, but typical and of the format studied in this course.

![Sensor system diagram](image)

Fig. 2.1 Sensor system

Depending on the type and level of sophistication, the “sensor” may contain the signal conditioner as well as the A/D converter and computer processing stages. Just as with much of the analog and digital electronic technologies abound, many sensors now incorporate parts of the larger system on a single chip. In this course, the six basic building blocks are treated. Various sensor stimuli and physical principles are utilized, signal conditioning circuits are constructed, and the resulting signal is computer interfaced. DC and stepper motors are utilized as the output or actuator stage. While this course was originally intended to educate engineering physics students about sensors, including the subsequent building blocks is
essential to appreciate the scope of sensors in practice.

Sensors may be classified in a number of ways, by the stimulus, physical principle employed, conversion phenomenon, device specifications, materials, or application. Not wanting this course to overly emphasize specific applications, material science, or device characterization techniques, we have opted to examine sensors based on the first two criteria; the stimulus and physical principle exploited. The conversion phenomenon is treated incidentally. Tables 2.1 and 2.2 are abbreviated lists of common stimulus and physical principles utilized in many sensor technologies. The vast amount of sensor technology today has made possible measurements of any one stimulus by numerous physical principles. The extraordinary diversity lends devices which fully span the categories of conversion phenomenon, specifications, materials, and applications.

### Table 2.1 Stimulus

<table>
<thead>
<tr>
<th>Category</th>
<th>Stimulus</th>
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<tr>
<td>Chemical</td>
<td>type or concentration of specie</td>
</tr>
<tr>
<td>Electric</td>
<td>current, voltage, conductivity</td>
</tr>
<tr>
<td>Magnetic</td>
<td>magnetic field strength or field pattern</td>
</tr>
<tr>
<td>Mechanical</td>
<td>position, speed, acceleration, force, strain</td>
</tr>
<tr>
<td>Optical</td>
<td>intensity, ray direction, ray position</td>
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<tr>
<td>Thermal</td>
<td>temperature, specific heat</td>
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### Table 2.2 Physical Principles

<table>
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<th>Physical Principle</th>
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<tr>
<td>Resistance</td>
</tr>
<tr>
<td>Capacitance</td>
</tr>
<tr>
<td>Inductance</td>
</tr>
<tr>
<td>Electromagnetic Induction</td>
</tr>
<tr>
<td>Photoelectric Effect</td>
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Sensors are unique electronically in that most devices are fabricated to be as immune as possible to the changing external environment. Great lengths are taken to insure stable operation over broad temperature ranges, vibration, electronic interference, device tolerances, and other influential factors. Sensors however, are in part, designed with the opposite strategy, to be as susceptible as possible to temperature, external electric and magnetic fields, mechanical vibration, and so-on. Every physical entity is in some way a sensor in that it will respond, some how, to some external influence. The many ways in which the stimulus and physical principles merge is partly responsible for the vast diversity of sensors in existence. Chemical species may be measured by influencing the resistance of a polymer slab or affecting the mechanical resonance of a metal plate. Position may be determine through a change in inductance, acceleration by means of a change in capacitance, or light intensity through a change in resistance. In creating a sensors course one is partly challenged not by deciding what
3. A Laboratory Course in Sensors

This is a senior level, undergraduate, 2-credit laboratory course about sensors and sensor systems. There are a number of experiments involving prototyping electronic circuits, using a variety of electronic instrumentation, writing computer code in Visual Basic (VB), data collection, graphing, analysis, and report writing. In addition to the experiments a term project is required which will include a written report and oral presentation. The course has been offered three times and while the scope of the course has not wandered it has evolved in terms of the balance amongst the time dedicated to the physics of sensors, experimental techniques, signal conditioning electronics, computer interfacing and programming. Presently, the specific objectives are:

1. To understand the fundamental mechanism exploited by a sample of the most common types of modern sensors: resistive, electromagnetic, optical, capacitive, and magnetoresistive. A research paper will also be required which discusses a contemporary sensor technology.

2. To understand how sensors may be used to measure position, velocity, acceleration, force, tilt, temperature, and magnetic field strength.

3. To gain practice in the use of op-amps and the Wheatstone bridge for signal conditioning small analog signals suitable for low-end A/D converters.

4. To further the practice of conducting experiments, utilizing state-of-the-art test and measurement instrumentation, interpreting data, device modeling and calibration, programming in Visual Basic, and computer interfacing.

5. To be able to control by PC both stepper and DC motors.

6. To further the practice of communicating the results of a project in writing and public speaking.

Objectives one and two have resulted from a number of issues. There are countless sensors available which span the range of sophistication, cost, package style, application, and other factors which must be considered when designing an experiment. The choice of sensor must consider the type of measurement instrumentation available (e.g. bandwidth or power), the means by which it’s inner components may be probed or exposed (i.e. package style), complexity or technological sophistication (e.g. we are not equipped to study SQUIDs), industrial popularity (i.e. something not esoteric), and cost. An attempt has been made to select those sensors which allow the following experimental steps to be completed within 4-6 hours:
4. Sensor Experiments

The following highlights the experiments performed in the Fall of 2000. A more thorough treatment of the sensors themselves may be found in reference 1.

4.1 Linear Variable Differential Transformer (LVDT)

The LVDT is an extremely familiar device in industry used to measure position or displacement. They are available as AC or DC output, strokes ranging from $10^{-6}$ to $10^{-1}$ meters, and are of the variable inductance type. A simple schematic is shown in figure 4.1.1. The ferromagnetic plunger is attached to the object of which the displacement is to be measured. The mutual inductance between the primary and secondary coils varies with the plunger’s position. The analysis of the equivalent circuit model shows that for a high impedance load the transfer function is given as,

$$e_{out} = s(M_2 - M_1)i_1$$

![Fig. 4.1.1 LVDT](image-url)
where \( M_2 - M_1 \) is the differential mutual inductance between the primary and one of the secondary windings and the primary and the other secondary winding, \( s \) the usual Laplacian operator, and \( i_1 \) the primary current. \( e_{out} \) is found to vary linearly with the plunger’s position. Both a commercial LVDT and home made LVDT are studied. The home made version consist of a glass tube wrapped with the three windings, a steel nail inserted within the tube and loaded on top with a caliper for measuring displacement and spring below for providing tension. With this simple apparatus the above model is tested as a function of frequency, input current amplitude, and output voltage amplitude as a function of plunger position.

For signal conditioning, these devices in practice utilize phase modulation/demodulation\(^2\) techniques to extract the amplitude and phase of the two secondary voltages. That being somewhat sophisticated, we have opted in this experiment to utilize a commercial LVDT with a DC output to discuss an application with computer interfacing. (The DC versions incorporate electronics internal to the device itself.) The commercial LVDT is mounted on top of an irregularly shaped object which rotates (Fig. 4.1.2.) . The linear displacement of the LVDT is then a mapping of the object’s contour from which center-of-mass and moment of inertia may be calculated.

![LVDT application](image)

**Fig. 4.1.2** LVDT application

### 4.2 Linear Velocity Transducer (LVT)

The LVT is also a very familiar sensor to industry and of the electromagnetic induction type. Its structure, and appearance, is much like the LVDT. Unlike the LVDT however, the LVT is an active device. Fig. 4.2.1 illustrates the basic components of the LVT in the form of how it is studied here. The commercial LVTs consist of a hermetically sealed tube incorporating two windings connected in series opposition. As a magnet passes through the windings a voltage develops according to Faraday’s Law of induction. The amplitude of the induced emf will be
proportional to the rate of change of the magnetic flux which is proportional to the plunger’s speed. The magnetic plunger itself however appears to be, by examining with a compass, two dipoles in series. As long as the plunger lies within the two coils the output voltage is proportional to the plunger’s speed. There are a number of very interesting factors which influence the signal from the two coils such as the spacing of the two coils and the spacing of the two magnets. The commercial LVTs do not reveal this information. This experiment thus involves an interesting exercise in studying a basic phenomenon, magnetic induction, in a way that challenges the students to optimize two of the variables, coil and magnet spacing, to achieve the output claimed by manufacturers of these devices. The experiment begins with simply sliding a single bar magnet down a tube through one coil and examining the induced emf on an oscilloscope. The experiment then progresses to two magnets and two coils with varying spacings amongst themselves. The reflective sensor is utilized for determining speed. An analytical model for this device is beyond the scope of the course, even beyond the scope of undergraduate engineering, thus students see the value of empirical evidence and the role of experiment in design. Students discover that the ‘best’ output results when the coil spacing and magnet spacing are matched.

4.3 Strain Gages

Strain gages are of the resistive type commonly used for measuring strain, force, and pressure. The strain gage consist of a thin film of conducting material applied to a film capable of being adhered to the strained member. As the member is strained, the strain gage will stretch (or contract) in a given direction, altering its electrical resistance. A fundamental characteristic of strain gages is the gage factor, $K$, defined as,
A typical value for $R$ is 120 $\Omega$, $K$ of 2, and a maximum strain (or yield) for (10-18 or 10-20) carbon steel of $10^3$ inches/inch. This gives a change in resistance of $0.24\Omega$. The basic operation of the strain gage is studied by mounting a linear strain gage on a cantilever beam which through a lead screw attached to a stepper motor is deflected (see figure 4.3.1.).

$$K = \frac{\Delta R}{R} = \frac{\Delta R}{\varepsilon} = \frac{R-R_0}{R_0}$$

The strain is then given by,

$$\varepsilon(x) = \frac{3xy_o}{2L^3}$$

where $x$ is the position of the strain gage relative to the lead screw (point of force), $y_o$ the deflection (controlled by the number of steps of the stepper motor and screw pitch), $t$ the beam thickness, and $L$ the distance from the lead screw to the opposite fixed end. Also, a relationship exist amongst the applied force $F$, modulus of elasticity $E$, and beam deflection $y_o$,

$$y_o = \frac{4FL^3}{Ewt^3}$$
Using the stepper motor, the change in resistance of the strain gage is measured as a function of the beam deflection. From this the gage factor is determined. Knowing the gage factor, modulus of elasticity, and beam geometry, the weight of an unknown mass may also be determined (left side of Fig. 4.3.1). This is a force sensor. If time permits, the strain gage is incorporated into a Wheatstone bridge, followed by an amplifier, and A/D converter. The output voltage is monitored through a VB program and calibrated to the unknown mass.

4.4 Position Sensitive Detector (PSD)

The PSD is a p-i-n photodiode with a relatively large anode surface (see Fig. 4.4.1).

They are available in a variety of sizes, one and two dimensional. A one dimensional version is shown above. There are three electrodes, one connected to the cathode and two on the ends of the anode. Depending on where a laser beam strikes the anode surface, varying currents arrive at the two anode contacts. A determination of these currents prescribes the beam spot location by,

\[
\frac{I_L - I_R}{I_L + I_R} = \frac{2x}{L}
\]

where \(I_L\) and \(I_R\) are the two currents, \(L\) the length of the anode, and \(x\) the position relative to the anode center where the laser beam strikes. Op-amps are used to convert these currents into voltages followed by a single stage amplifier, and A/D converter. While the length \(L\) is given by the manufacturer, it is easily verified experimentally.
PSDs are used for auto-focus cameras as well as in instruments for small displacement measurements. We have contrived an experiment using the PSD and ray tracing to determine the focal length of a spherical mirror. The experiment is shown in Fig. 4.4.2. The mirror is mounted on a stage driven by a stepper motor. As the mirror position changes, so does the position of the beam on the PSD. A ray tracing model relates these quantities as,

\[ \Delta r = \left( \frac{r_{in}}{f} - \frac{2r_{in}}{y_o} \right)(y - y_o) + \frac{r_{in}}{fy_o}(y - y_o)^2 \]

where \( \Delta r \) is the distance from the PSD center, \( y_o \) the distance along the y-axis when \( \Delta r \) is zero, \( r_{in} \) the entrance position of the laser beam, and \( f \) the unknown focal length. Once the PSD is calibrated \( \Delta r \) is easily monitor along with \( y \), again through VB code, and \( r_{in} \) and \( y_o \) may be measured with a ruler. (The ratio \( r_{in} / y_o \) may be determine nicely by using a flat mirror!).

Fig. 4.4.2  PSD experiment
4.5 Magnetoresistive Sensor

These sensors are of the resistive type, where the resistance varies with applied magnetic flux. They are available in one, two, and three dimensional packages. The devices we have employed are one dimensional units which come in a four terminal IC where the four leads connect to the four points of a Wheatstone bridge. Each resistor of the bridge is a magnetoresistive element. Applying a magnetic flux up to ~ 6 G results in a bridge output of ~ 20 mV. This one dimensional unit is studied by monitoring the output voltage as the device travels towards and within a coil. By calibrating the resulting voltage with position, a position sensor is made. We have also studied a three dimensional unit. These devices offer three magnetoresistive detectors with signal conditioning electronics on a single module (approximately 1.2 cm x 2.5 cm). The output consists of three voltages corresponding to the x, y, and z components of the magnetic flux. Placing this unit of an XY-stage which travels relative to a fixed magnet demonstrates a means of mapping the magnetic field.

4.5 Electrolytic Tilt Sensor

The electrolytic tilt sensor consists of a tubular glass envelope partially filled with an electrolytic fluid and metal electrodes (see Figure 4.5.1). A variety of tilt sensors are manufactured and characterized by the envelope geometry, electrolyte, and electrode configuration. There exists an impedance between the electrodes which varies with the tilt. The relation between the impedance and the tilt is nonlinear, as you will observe. There are vast applications for this relatively simple device. Electrolytic tilt sensors have been used in submarine dive and leveling transducers, aircraft flight control, virtual reality, oil rig leveling and bore angling, construction laser instruments, machine tool leveling, and digital compass correction.

The first exercise in this experiment is to measure the AC resistance as a function of tilt. Students are then challenged to explain the result. The device does not behave like a linear resistor \( R = rL/A \). The device is then computer interfaced by constructing a Wheatstone bridge, amplifier, peak detector, followed by an A/D converter.

4.6 Accelerometer

A capacitive type accelerometer is studied. This device consist of a micromachined transducer in the form of two capacitors as illustrated in figure 4.6.1. The device is available in a 16-pin
DIP package with extensive signal conditioning electronics. The device offers a sensitivity of 50 mV/g with a range of +/- 40 g. The experiment consist of mounting the accelerometer on a cantilever beam along with an eccentrically loaded motor (see figure 4.6.2). The eccentric load consist of a disc on both sides of the motor which has a hole off center.

Fig. 4.6.1 Accelerometer

Fig. 4.6.2 Accelerometer apparatus

4.7 Temperature Sensor

A very common temperature sensor is the LM335. This device is a diode with a fine tuned temperature dependent reverse breakdown voltage. The basic circuit is shown in figure 4.7.1. The experiment using this device was actually introduced as a means of demonstrating VB programming, controlling stepper motors, and calibrating a sensor. The LM335 is a three terminal device which is sealed within heat shrink to form a water tight probe.

Fig. 4.7.1 Temperature sensor

Firstly, the sensor is calibrated and a model synthesized. The instructor gives each student a model for which they are to write VB code to control a stepper motor to position itself according to the temperature of a water bath. As the water bath temperature climbs, the motor
shaft positions itself according to the assigned model. The physics of this device are not studied extensively, rather the device serves as a platform for demonstrating basic issues of a sensor system.

4.8 DC and Stepper Motors

Most students entering the sensors laboratory course are not familiar with stepper motors nor means of driving DC motors other than using a switch or single transistor. So that some form of actuator may be included in the sensor systems, students learn how to drive 4-phase stepper motors and DC motors using stepper driver and H-bridge integrated circuits. These circuits are computer interfaced and controlled through their own VB code. The use of DC motors also provides the platform for exposing students to encoder wheels and frequency-to-voltage converters for measuring angular speed. Including motors as part of the experiments further supports the term projects in that students are better equipped to include some form of mechanical motion in their sensor systems.

5. Term Projects

The last three weeks are dedicated to term projects. Teams of 3-4 are formed with each team conceiving, designing, constructing, and demonstrating their own sensor system. The sensor system they construct must incorporate 1) at least one sensor, 2) one actuator, 3) operate autonomously, and 4) serve a clearly stated function. (Kits are not accepted.) The project also requires a project proposal and final written and oral reports. Beyond the minimum requirements they are judged on the basis of ingenuity, sophistication, creativity, and functionality. In the past students have constructed line followers, vehicles which follow a moving magnet, tilt sensors, light driven vehicles, and strain gage controlled vehicles.

6. Conclusion

The sensors laboratory course has been offered now three times. Early on in developing this course, it was discovered that if there exist a model sensors course, it is not easily identified. Furthermore, the many engineering education companies who manufacture experimental apparatus do not offer sensor apparatus sufficient and appropriate for our objectives. The apparatus we have used is all home made. Some of the sensors themselves are home made. Much of the sensor technologies available commercially are packaged in such a way to not be apparent. Avoiding the ‘black box’ approach has been a pedagogical objective from the beginning.

Our approach to this course was first to establish how amongst all the sensor technologies available could a small sample be studied and still inflict on the student the techniques and issues of all sensors and sensor systems. We did not want an esoteric sensors course, but rather a generalized sensors course. We chose those sensors which were common, did not require
specialized equipment to study, where either affordable or could be fabricated, were conducive to a home made apparatus for experiments and applications, and represented several of the basic physical stimulus and device principles.

To complete the scope of sensors in practice, we also include signal conditioning and computer interfacing within most of the experiments. DC and stepper motors are also covered and serve as the actuators. The prerequisites for this course are basic AC and DC circuits and a first course in modern physics. The signal conditioning circuits employed do not extend beyond the Wheatstone bridge and various op-amp circuits (differential amplifiers and peak detectors). The A/D converters used are low-end devices and require a minimal amount of software code. Visual Basic is now the program of choice for the computer interfacing. VB is well known in industry and while many students have not programmed in any kind of Basic, their experience with C++ is sufficient (with some additional guidance from the instructor).

Students completing this course acquire at a minimum a basic working knowledge of seven different sensors representing different stimulus and physical principles, practical hands-on experience with op-amps, computer interfacing issues, VB programming, sensor calibration, motor control electronics, exposure to, and design of multidisciplinary systems.

Bibliography
1. Fraden, Jacob Handbook of Modern Sensors, 2nd Edition, AIP Press 1996. This is likely the most cited text on sensors.

W. Doyle St.John
Doyle St.John is an assistant professor of Engineering Physics at the University of Wisconsin - Platteville. He holds a B.S. and M.S. degree in Electrical Engineering and a Ph.D. in Physics. After a post-doctoral experience at the Liquid Crystal Institute in Kent, Ohio he worked as an optical physicist in the area of flat panel displays. Presently, his interest are sensors and sensor systems.