Industrial Electronics
Transducer Fundamentals

Student Workbook
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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

♦ The unit objective
♦ Unit fundamentals
♦ A list of new terms and words for the unit
♦ Equipment required for the unit
♦ The exercise objectives
♦ Exercise discussion
♦ Exercise notes

The Appendix includes safety information.
**UNIT 1 – FAMILIARIZATION**

**UNIT OBJECTIVE**
At the completion of this unit, you will be able to describe the basic operation of transducer devices. You will be able to locate and describe the functions of the circuit blocks on your TRANSDUCER FUNDAMENTALS circuit board.

**UNIT FUNDAMENTALS**
Electronic computer and control circuits have become the backbone of modern industry because of their speed, accuracy, reliability, and cost-efficiency.

Electronic circuits can quickly process information that is introduced to the system by way of input media such as keyboards, switches, and external communications interfaces.

Output devices include displays for feedback to human operators and control circuits to control machinery and/or processes.

Another type of input medium is the **transducer**. A transducer is a device that converts one form of energy into another.

There are two basic transducer types: **input transducers** and **output transducers**.

Input transducers, which are also sometimes called **sensors**, convert a physical quantity into a proportional electrical signal that can be input into an electronic circuit.

Output transducers convert an electrical signal into a physical quantity that can be detected or used externally.
The left side of this table shows examples of the physical quantities that input transducers convert into electrical signals. The right side shows physical quantities that output transducers convert electrical signals into.

You can find many examples of transducers in everyday life. The thermostat in your home has an input transducer that senses room temperature and is used to control heating and air conditioning.

Many streetlights are equipped with photosensors that are used to turn the lights on when the sun goes down.

A speaker is an output transducer that converts electrical signals into sound energy.

In Exercise 1 of this Unit, you will learn the fundamental operation of transducer devices. You will apply this knowledge by measuring basic transducer parameters on your TRANSDUCER FUNDAMENTALS circuit board.

In Exercise 2, you will become familiar with the eight transducer circuit blocks and three auxiliary blocks on your circuit board. You will examine and demonstrate typical transducer circuits and how they are applied in practical situations.

**NEW TERMS AND WORDS**

**transducer** - a device that converts one form of energy into another.

**temperature coefficient** - a factor used to calculate the change in the characteristics of a device with changes in its temperature.

**positive temperature coefficient** - a temperature coefficient that indicates that a device’s output parameter increases as temperature increases.

**negative temperature coefficient** - a temperature coefficient that indicates that a device’s output parameter decreases as temperature increases.

**sensors** - input transducers that detect non-electrical physical quantities.

**input transducers** - transducers that convert a non-electrical physical quantity into a proportional electrical signal.

**output transducers** - transducers that convert an electrical output signal into a non-electrical physical quantity.
EQUIPMENT REQUIRED
F.A.C.E.T. base unit
TRANSDUCER FUNDAMENTALS circuit board
Power supply, +15 Vdc and -15 Vdc (2 required)
Multimeter
Oscilloscope, dual trace

NOTES
Exercise 1 – Introduction to Transducers

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to describe the basic operation of transducer devices. You will verify your results by measuring basic transducer output parameters.

DISCUSSION
Different input transducers have different electrical outputs. For example, the thermocouple produces an output voltage; the IC temperature transducer produces an output current, and the thermistor produces an output resistance.

The CAPACITANCE SENSOR circuit block uses a transducer that produces an output that is a change in capacitance.

The transducer output can be measured directly or fed into additional circuitry to perform one or more of these functions:

- amplify the signal
- scale the signal
- convert the signal
- convert the measuring units

Another consideration in the selection and use of transducers includes the linearity of the response and whether the output parameter increases or decreases with respect to the input parameter.
Exercise 2 – Introduction to the Circuit Board

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to locate and describe the operation of the various circuit blocks on your TRANSDUCER FUNDAMENTALS circuit board. You will verify your results by making interconnections and taking measurements.

DISCUSSION
- There are eight different types of transducers on the TRANSDUCER FUNDAMENTALS circuit board. They are:
  - IC TRANSDUCER
  - THERMISTOR
  - RTD
  - THERMOCOUPLE
  - STRAIN GAUGE
  - CAPACITANCE SENSOR
  - ULTRASONIC TRANSDUCER
  - INFRARED CONTROLLER
- There are three auxiliary circuit blocks which are used in the operation of the transducer circuitry. These auxiliary blocks are:
  - REFERENCE SUPPLY
  - INSTRUMENTATION AMPLIFIER
  - OVEN
- The REFERENCE SUPPLY converts the + and – 15 Vdc from the F.A.C.E.T. base unit to a regulated reference voltage of + and – 5 Vdc, and + and – 0.5 Vdc.
- The INSTRUMENTATION AMPLIFIER is used to amplify the output of the transducer circuits.
- The INSTRUMENTATION AMPLIFIER’s gain can be selected using a DIP switch. There are four gain settings.
- The INSTRUMENTATION AMPLIFIER circuit block has jacks that can be used as test points and/or making connections. Three jacks are on the input side.
- The OVEN consists of eight resistors that are wired in series forming a heating element. The oven components are enclosed in a clear plastic sealed cover to create a controlled air space for experiments.
- The IC TRANSDUCER, THERMISTOR, THERMOCOUPLE, and RTD are located inside the oven. These are temperature transducers sense heat to produce an output parameter.
- Temperature measurement circuits require calibration for precise operation.
• Transducers have different properties and characteristics that are used to determine their suitability to particular applications. Examples include: output type, operating range, linearity, stability, and cost.
• The STRAIN GAUGE circuit block has a transducer mounted to a thin metal beam in a fixture. A strain gauge measures the strain on the surface of the object to which it is attached.
• Transducers can be used as touch sensors, proximity detectors, position sensors, and displacement measuring devices. The CAPACITANCE SENSOR circuit block is used to illustrate these applications.
• The capacitance sensor converts mechanical motion into an electrical signal. It consists of a fixed and movable plate. The fixed plate is solid copper which is etched onto the circuit board. The movable plate’s position is indicated by the scale located on the left guide; the scale is in centimeters.
• The ULTRASONIC TRANSDUCER circuit block has separate TRANSMITTER and RECEIVER sections. There is an ultrasonic transducer on each section.
• Ultrasonic transducers can be used to measure distance.
• The INFRARED CONTROLLER circuit block uses infrared light to send and receive digital codes. Familiar applications of infrared sensors are in wireless remote control of TVs, VCRs, and stereos.
• The INFRARED CONTROLLER circuit block has separate RECEIVER and TRANSMITTER sections.
• A 4-bit binary code can be set using the DIP switches located on the TRANSMITTER section. This parallel data is converted into serial data and is transmitted by an infrared LED.
• The RECEIVER section has an infrared-sensitive transducer that detects the transmitted signals. The board’s circuitry performs the conversion of the data and displays it on a group of four LEDs.
UNIT 2 – IC TEMPERATURE TRANSDUCER

UNIT OBJECTIVE
At the completion of this unit, you will be able to explain the operation of the IC temperature transducer and its function as a temperature measurement and control device.

UNIT FUNDAMENTALS

The IC temperature transducer used on your circuit board is an epoxy-encapsulated integrated circuit.

Although it is packaged in a 3-terminal TO-92 case, the transducer itself is a 2-terminal device. The center lead is not internally connected.

The IC functions as a current source whose output current is a function of temperature.

At a reference point of 0°C (the freezing point of water), the output current (I_{REF}) is 273.2 µA.

Every temperature transducer has a temperature coefficient that describes the way the transducer’s characteristics change as temperature changes.
The temperature coefficient $\alpha$ (the Greek letter alpha) of the IC transducer on your circuit board is one microamp per degree Celsius ($\alpha = 1 \, \mu\text{A/}^\circ\text{C}$).

A positive or negative temperature change from the $0^\circ\text{C}$ reference point causes a positive or negative current change of $1 \, \mu\text{A/}^\circ\text{C}$.

For any temperature $T$, the current at that temperature ($I_T$) may be expressed as follows:

$$I_T = (\alpha \times T) + 273.2 \, \mu\text{A}$$

(where $I_T$ is in $\mu\text{A}$, $T$ is in $^\circ\text{C}$, and $\alpha = 1 \, \mu\text{A/}^\circ\text{C}$).

This figure shows the output characteristics, schematic symbol, and a list of advantages and disadvantages for the IC temperature transducer.

The advantages and disadvantages are relative to the other types of temperature transducers on your circuit board. For example, the IC transducer has the highest output level as compared to the thermocouple, thermistor, and RTD.

The IC temperature transducer on your circuit board has a positive temperature coefficient. This means that the transducer's temperature-dependent parameter (current) increases as temperature increases.
This is a simplified block diagram of the IC TRANSUDER circuit block. The transducer's current output \([I(T)]\) drives an op amp that is configured as a current-to-voltage converter. The resulting output is a voltage \([V(T)]\) that is a function of the transducer's temperature. The remaining circuitry allows the block to operate as a temperature controller that regulates the temperature inside the oven.

Resistor \(R_{SP}\) is used to select a **set point**, or the temperature at which the oven is to be regulated. A second op amp, configured as a comparator, determines whether the oven temperature is above or below the set point.

The comparator's output drives a transistor that switches a heater resistor on if the temperature is below the set point, or off if the temperature is above the set point.

**NEW TERMS AND WORDS**

*IC temperature transducer* - an integrated circuit that outputs a voltage or current that is a function of temperature.

*temperature coefficient* - a factor used to calculate the change in the characteristics of a device with changes in its temperature.

*positive temperature coefficient* - a temperature coefficient that indicates that a device's output parameter increases as temperature increases.

*negative temperature coefficient* - a temperature coefficient that indicates that a device's output parameter decreases as temperature increases.

*set point* - the desired value at which a temperature controller is to regulate temperature.

*on/off controller* - a temperature controller that turns the heating element fully on below the set point and fully off above the set point.

**EQUIPMENT REQUIRED**

F.A.C.E.T. base unit

TRANSUDER FUNDAMENTALS circuit board

Multimeter

Oscilloscope, dual trace
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Exercise 1 – Temperature Measurement

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to explain and demonstrate the use of an IC temperature transducer in a temperature measurement application.

DISCUSSION
• An op amp is used to output a voltage that is the difference between two input currents.
• The two input currents are summed at the op amp’s inverting terminal.
• One current is a fixed calibrated current used to establish a temperature-to-voltage conversion factor.
• The second current source is the IC temperature transducer (AD1). The IC temperature transducer outputs a current that is a linear function of its temperature.
• The transducer’s current can be calculated for any temperature by using this equation:
  \[ I_{AD1} = (\alpha \times T) + 273.2 \mu A \]
  where: \( \alpha \) is the transducer’s temperature coefficient (1 \( \mu A/°C \))
  273.2 \( \mu A \) is the device’s reference current at 0 °C
• The op amp’s output voltage, at any temperature, can be determined by the following equation:
  \[ V_{OUT} = (I_{AD1} - 303.2 \mu A) \times R_{FB} \]
  where: \( I_{AD1} \) is the transducer current (in \( \mu A \)) at the desired temperature.
  303.2 \( \mu A \) is the transducer’s current at the 30°C calibration temperature.
  \( R_{FB} = 500 \, k\Omega \)
• Since the circuit is designed for a temperature-to-voltage conversion factor of 0.5V per °C this equation can be used to calculate output voltage:
  \[ V_{OUT} = (T - 30 \, ^{°}C) \times 0.5V/^{°}C \]
• The IC temperature transducer’s current or the converter’s output voltage can be measured and used to determine temperature.
Exercise 2 – Temperature Control

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to demonstrate how you can use the IC temperature transducer to control the temperature inside the OVEN.

DISCUSSION
- The input to the temperature controller is the output voltage \([V(T)]\) from the current-to-voltage converter.
- Current is a function of the IC transducer’s temperature.
- The op amp (U1B) compares the current through \(R_I\) to the current through the set point resistor \(R_{SP}\).
- The current through \(R_I\) is a function of temperature since it is generated by the output voltage \([V(T)]\) of the current-to-voltage converter.
- The set point resistor \(R_{SP}\) is connected to \(-5V\).
- The shunt, located on the TEMP header, is used to select one of four set points.
- As the oven temperature varies slightly above and below the set point, the comparator input varies slightly above and below 0V.
- When the oven temperature falls below the set point, the comparator output enables transistor driver (Q1), which turns on the heater and the indicator LED.
- When the oven temperature rises above the set point, the comparator output is low and drives transistor Q1, the heater, and the LED are off.
- The two diodes and the Zener diode, in the negative feedback loop, clamp the voltage to \(+5.5V\) for a high level, and \(-1.1V\) for a low.
- The capacitor in parallel with \(R_I\) causes the comparator to switch before the oven temperature reaches the set point.
- A change in \(V(T)\) causes a change in oven temperature by controlling the heater.
- The transducer senses a change in oven temperature, and causes \(V(T)\) to change, thereby forming a closed loop.
UNIT 3 – THE THERMISTOR

UNIT OBJECTIVE
At the completion of this unit, you will be able to describe and demonstrate the characteristics and operation of a thermistor.

UNIT FUNDAMENTALS
A thermistor is a two-wire temperature transducer whose resistance is a function of temperature. The thermistor's schematic symbol is similar to that of a resistor, except that the symbol $t^\circ$ is used to indicate temperature dependence.

![Thermistor Symbol and Graph](image)

Although most thermistors, including the one on your circuit board, have a negative temperature coefficient, positive types are also available.

Thermistors are popular temperature transducers because of their high output, or relatively large resistance change per degree.

Self-heating is a disadvantage for several temperature transducers, including thermistors. Self-heating is a device's tendency to heat up beyond its surrounding (ambient) temperature due to its own power dissipation.

![Thermistor Image](image)

Thermistors are packaged in many different configurations, including disc, bead, and chip styles.

The device used on your circuit board is an epoxy-coated chip thermistor.
A typical thermistor temperature measuring circuit uses the thermistor in a Wheatstone bridge configuration. The bridge output drives an instrumentation amplifier whose output voltage is a function of the thermistor's temperature. You can select amplifier gain and component values for the desired relationship of output voltage to temperature.

NEW TERMS AND WORDS

thermistor - a temperature transducer made of semiconductor material whose resistance is a function of temperature.

self-heating - a device's tendency to heat up beyond its ambient temperature due to internal power dissipation.

Resistance-Temperature (RT) table - a set of manufacturer's data that tabulates a thermistor's resistance ratio and other parameters at specific temperatures.

resistance deviation - a percent deviation of a thermistor's resistance at a specific temperature $T$. Resistance deviation is added to the thermistor's resistance tolerance at a reference temperature to determine the overall tolerance at the specific temperature, $T$.

resistance ratio - a thermistor's resistance at a specific temperature divided by its resistance at a reference temperature.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
TRANSUDER FUNDAMENTALS circuit board
**Exercise 1 – Thermistor Characteristics**

**EXERCISE OBJECTIVE**
When you have completed this exercise, you will be able to describe and demonstrate the characteristics of thermistors.

**DISCUSSION**
- A thermistor is a semiconductor temperature transducer whose resistance is a non-linear function of temperature.
- Each thermistor type has a different curve of resistance ratio versus temperature.
- The curves differ depending on the thermistor material, size, and physical configuration.
- To use the curve the resistance ratio for the transducer must be found. The manufacturer supplies a Resistance-Temperature (RT) table with each device.
- Resistance deviation varies with temperature and is used to determine the overall resistance tolerance.
- For thermistors, the temperature coefficient ($\alpha$) is a percent resistance change per degree C (%/°).
- Self-heating is the thermistor’s tendency to heat up beyond its ambient temperature due to the device dissipating power.
- The amount of a thermistor’s self-heating is specified by its dissipation constant (DC). The dissipation constant is the ratio (measured in mW/°C) of the change in the device’s power dissipation to the resultant body temperature change. The thermistor on this circuit board has a DC of 1 mW/°C at 25 °C.
- For a thermistor with negative temperature coefficient, self-heating results in decrease resistance and a corresponding increase in current and power.
Exercise 2 – Temperature Measurement

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to explain and demonstrate the use of a thermistor in a temperature measurement circuit.

DISCUSSION
- Since the thermistor is a resistive device, it is easily used in resistance bridge configurations for temperature measurement applications.
- The THERMISTOR circuit block contains a Wheatstone bridge. The bridge sensitivity is designed for 5 mV/°C when calibrated.
- The output of the bridge is connected to the instrumentation amplifier. The instrumentation amplifier is set for a gain of 100.
- When the circuit is calibrated the amplifier output is 0V at a 30°C reference temperature.
- This equation is used to calculate the temperature (T): \( T = \frac{V_{\text{OUT}}}{0.5} + 30 \)
UNIT 4 – THE RTD

UNIT OBJECTIVE
At the completion of this unit, you will be able to explain and demonstrate the characteristics of the resistance temperature detector (RTD) and its application in a practical temperature measurement circuit.

UNIT FUNDAMENTALS

The resistance temperature detector (RTD) is a temperature transducer whose resistance is a function of temperature.

RTDs have a resistive wire element and are usually manufactured using thick- or thin-film technology. The RTD on your circuit board is a thin-film device with a platinum resistance element in a two-lead ceramic package.

Because of the resistance-temperature relationship, the RTD schematic symbol is similar to that of the thermistor. The curve is not perfectly linear, but the RTD’s linearity is good compared to other transducers such as thermistors and thermocouples.
RTDs are the most stable and accurate temperature transducers. Their disadvantages include high cost and a relatively small resistance change with temperature. As with thermistors, the resistive nature of RTDs allows their use in resistance bridge circuits for temperature measurement applications.

An alternative method is a resistance-to-voltage converter. The converter shown is used on your circuit board and has an op amp with the RTD in the feedback loop.

The op amp outputs a voltage that is a function of temperature. Component values are selected to establish the desired relationship of output voltage to temperature, and a potentiometer is included for calibration.

NEW TERMS AND WORDS
None

EQUIPMENT REQUIRED
F.A.C.E.T. base unit
TRANSUDER FUNDAMENTALS circuit board
Exercise 1 – RTD Characteristics

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to explain and demonstrate the transducer characteristics of the resistance temperature detector (RTD).

DISCUSSION
• Using RTDs as temperature transducers developed because the resistance of metals increases as their temperature increases.
• The first RTD design used coils of wire. The most commonly-used material are highly resistive metals such as platinum, nickel, and tungsten.
• Manufactures use thick- or thin-film technology to deposit the precise amount of metal film onto the ceramic substrate.
• Manufactures supply an RTD table with each device. The table is used to determine resistance at a specific temperature. The actual resistance is listed – not a resistance ratio.
• The temperature coefficient for the RTD on the circuit board is 0.00385.
Exercise 2 – Temperature Measurement

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to explain and demonstrate the use of an RTD in a temperature measurement application by using a resistance-to-voltage converter circuit.

DISCUSSION
- A resistance-to-voltage converter in the RTD circuit block is used with the RTD for the temperature measurement application.
- There is a constant current that flows through the input resistor (R4). Adjusting the voltage across R4 with the potentiometer (R2) calibrates the current.
- Since the current through the RTD is constant, the op amp’s output voltage depends on the RTD’s resistance.
- The RTD’s resistance changes with temperature; therefore, the output voltage is a function of temperature.
- The output voltage is 0V at a reference temperature of 30°C. The circuit is calibrated for an output of 5 mV/°C.
- This equation is used to calculate the output voltage:
  \[ V_{OUT} = (T - 30) \times 0.005 \]
- For larger output voltage levels, the resistance-to-voltage circuit is connected to the instrumentation amplifier set for a gain of 100.
- When the instrumentation amplifier is used, the equation for output voltage becomes:
  \[ V_{OUT} = (T - 30) \times 0.5 \]
UNIT 5 – THE THERMOCOUPLE

UNIT OBJECTIVE
At the completion of this unit, you will be able to describe and demonstrate the operation of a thermocouple.

UNIT FUNDAMENTALS

A thermocouple is a temperature transducer consisting of two wires made of different metals soldered or welded together.

The junction of the two wires exhibits a phenomenon called the Seebeck Effect, whereby the junction generates a voltage that is a function of its temperature. Different combinations of metals result in different voltage-temperature characteristics. In industry, thermocouples are usually classified by a one-letter type designation that describes their response.

This figure shows the voltage-temperature curves and wire compositions for thermocouple types R, K, J, and E.

The THERMOCOUPLE block on your circuit board uses a J type device, which is composed of iron and constantan.
If you attempt to measure a thermocouple’s output with a voltmeter, the copper meter leads contact the thermocouple leads and form two additional junctions. Since the metals are dissimilar, each of these measuring junctions also produces a Seebeck Effect voltage that is dependent on temperature. The voltages at these junctions must be subtracted from the meter reading to obtain the true voltage at the sensing junction.

This figure shows how you can use a thermistor bridge circuit to cancel the effects of the Seebeck voltages at the measuring junctions. The temperature of the measuring junctions must be known in order to determine their voltages and subtract them from the meter reading. For this reason, the thermistor is placed in the same thermal environment as the measuring junctions so that it is at the same temperature.

The sensitivity and polarity of the bridge are designed to cancel the Seebeck voltages at the measuring junctions. The meter then reads only the desired voltage at the sensing junction.

NEW TERMS AND WORDS

**thermocouple** - a temperature transducer composed of two wires of dissimilar metals welded or soldered together.

**Seebeck Effect** - a phenomenon by which a soldered or welded junction of two dissimilar metals generates a voltage that is proportional to the temperature of the junction.

**measuring junctions** - the points in a thermocouple circuit at which the thermocouple wires are contacted by leads from a meter or other measuring circuit.

**sensing junction** - the junction in a thermocouple circuit whose voltage is measured to determine temperature.

**reference junction** - a measuring junction in a thermocouple circuit whose temperature must be known in order to correctly read the voltage at the sensing junction.

**electronic ice point reference** - a reference junction that is maintained at 0°C (the freezing point of water) or that outputs the equivalent 0°C voltage.
EQUIPMENT REQUIRED
F.A.C.E.T. base unit
Multimeter
TRANSUDER FUNDAMENTALS circuit board

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Exercise 1 – Thermocouple Characteristics

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to describe and demonstrate the characteristics of a thermocouple. You will verify your results with a multimeter.

DISCUSSION
• The schematic symbol of a thermocouple reflects its construction – two wires joined at their ends.
• The thermocouple’s response is nearly linear and is considered linear over small temperature ranges.
• Thermocouples are considered self-powered devices because they generate a voltage.
• Thermocouples are simple, rugged, low-cost transducers that operate over a very wide temperature range.
• Disadvantages include a low output level, stability, sensitivity, and the need for a reference for accurate temperature measurement.
• Manufacturers supply tables of voltage versus temperature for their thermocouples.
• The thermocouple on the circuit board has a linear response over the trainer’s operating temperature range. Therefore, its temperature coefficient ($\alpha = 51 \mu V/^\circ C$) can be used to calculate voltage at a given temperature.
• On this circuit board, the thermocouple is connected in a thermistor bridge.
• The thermistor and the measuring junctions are located on the underside of the circuit board so that they are in the same temperature environment.
• The bridge is adjusted to offset the effects of the measuring junction voltages. This configuration is called a reference junction circuit.
• When the bridge is balanced, its output voltage equals the thermocouple’s voltage at $0^\circ C$. Since $0^\circ C$ is the freezing point for water, the circuit is called the electronic ice point reference.
• The bridge output is connected to the instrumentation amplifier, set to a gain of 100, to increase the voltage to more practical levels.
• The following equation is used to determine the circuit output at any temperature $T$:
  \[ I_{A\ OUT} = \alpha \times T \times A_{V} \]
Exercise 2 – Temperature Measurement

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to explain the use of a thermocouple in temperature measurement applications.

DISCUSSION
- The circuit uses an instrumentation amplifier (IA) to drive a second op amp whose gain and offset are used to establish the relationship of output voltage to temperature.
- The components on this circuit board are selected for a factor of 0.5 V/°C.
- The voltage divider in the non-inverting input circuit allows for adjustment of temperature offset.
- Temperature (T) can be calculated from the output voltage using this equation:
  \[ T = \left( \frac{V_{OUT}}{0.5} \right) + 30 \]
- The circuit board has provisions to demonstrate an ice point reference temperature that is different from the thermocouple measuring junction temperature.
- The two-post connector in the HEATER position in the THERMOCOUPLE circuit block controls the current flow through a resistor that is thermally connected to the thermistor in the electronic ice point reference circuit. As the resistor heats up, it increases the thermistor’s temperature and a measurement error results.
UNIT 6 – THE CAPACITANCE SENSOR

UNIT OBJECTIVE
At the completion of this unit, you will be able to describe and demonstrate the operation of a capacitance sensor as a touch sensor and a position transducer.

UNIT FUNDAMENTALS

The structure and nature of a capacitor allow its use as a simple transducer that can measure position or displacement (the distance an object has moved).

A capacitor is composed of two parallel metal surfaces called plates. Between the plates is a dielectric, or insulating material. Commonly used dielectrics include air, paper, mica, and ceramics.

The capacitance of the device is a function of the surface area of the plates, the spacing between the plates, and the dielectric material. In this unit, the dielectric and the spacing do not change, so you can consider the capacitance to be a function of only the plate surface area.

More specifically, the amount of capacitance depends on the amount of surface area of one plate that overlaps the opposite plate.

For example, suppose the capacitor on the left has air as a dielectric. The two plates are equal in size and all edges are lined up. Assume that the position of the top plate is fixed and the bottom plate moves from position A to position B as shown on the right.
The fixed and movable plates compose a variable capacitor that you can consider a **capacitance sensor**. As you vary the amount of overlapping surface area by moving the plates, you also vary the amount of capacitance.

One application of the capacitance sensor is a **position sensor**. You can determine the position of the movable plate anywhere in its travel by measuring the capacitance at that position.

Another way you can change the amount of capacitance is by physically touching one plate of the capacitor.

The inherent capacitance of your body appears in parallel with that of the sensing capacitor. The total capacitance is then the sum of your body capacitance and the capacitance of the sensing device.

\[
C_{TOTAL} = C_{BODY} + C_{SENSE}
\]

The capacitance change can be detected by external circuitry or a measuring instrument. A capacitance sensor used in this way is a **touch sensor**.

This block diagram shows how you can use the capacitance sensor as either a touch sensor or position sensor. The sensing capacitor (\(C_S\)) and a timing resistor (\(R_T\)) are connected to an IC to form an RC oscillator circuit.

The output frequency (\(f_O\)) is a function of the RC time constant of the input components. Since changing the position of the sensor's movable plate changes the capacitance, \(f_O\) is a function of position.
You can use the circuit as a touch sensor by observing the change in output frequency when the capacitor plate is touched.

**NEW TERMS AND WORDS**

*displacement* - the distance an object has moved.

*capacitance sensor* - a transducer that can detect proximity, touch, position, or displacement by sensing a change in capacitance.

*position sensor* - a transducer that senses the position of an object.

*proximity detector* - a transducer that can sense the presence of a nearby object.

*touch sensor* - a transducer that detects a human touch by sensing body capacitance.

**EQUIPMENT REQUIRED**

- F.A.C.E.T. base unit
- Multimeter
- Oscilloscope, dual trace
- TRANSDUCER FUNDAMENTALS circuit board
Exercise 1 – Touch and Position Sensing

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to describe and demonstrate the use of a capacitance sensor as a touch sensor and a position transducer.

DISCUSSION
- The integrated circuit (ICM7555) is a timer that is configured as a free-running oscillator.
- The sensing capacitor (Cₚ) repeatedly charges through R₂ and R₃ and then discharges through R₃.
- The timer’s output is a square wave whose frequency is a function of Cₛ, R₂, and R₃.
- If CS is a variable capacitor, the circuit’s output frequency is a function of the position of the movable plate.
- The human body has an inherent capacitance. This property allows the CAPACITANCE SENSOR circuit to be used as a touch sensor.
- When the capacitor plate is touched, the body capacitance adds to that of the sensor. This larger total capacitance causes the circuit’s frequency to decrease.
- Observing the circuit’s output frequency with an oscilloscope or frequency counter will allow the detection of capacitance changes created by human touch.
- Capacitance changes occur if a finger is placed near, but not touching the capacitor plate. This property allows the sensor to be used as a proximity detector.
- In practice, the proximity detector often replaces mechanical switches since there are no moving parts to wear out.
UNIT 7 – THE STRAIN GAUGE

UNIT OBJECTIVE
At the completion of this unit, you will be able to explain and demonstrate typical strain gauge characteristics and the measurement of compressive and tensile strain by using the strain gauge fixture on your circuit board. You will verify your results with a multimeter.

UNIT FUNDAMENTALS
Many applications in industry require a transducer that can convert various forms of applied force into an electrical signal for measurement. A strain gauge is a type of input transducer that fulfills this requirement.

A strain gauge's resistance is a function of strain which is the amount by which a solid deforms under stress. Stress is a force that acts on a solid's unit area and causes a deformation of the solid.

Strain gauge applications include the measurement of weight, linear displacement, linear position, acceleration, force, torque, vibration, and pressure.

The operation of a strain gauge is based on the reaction of a conductor when strain is applied to it. The figure on the right shows the normal shape of a conductor (white lines), and the shape the conductor assumes when tension is applied (cyan lines).

When a conductor is under sufficient tension, its length increases and its cross-sectional area decreases. As a result, the conductor's electrical resistance increases. This is an example of tensile strain, or positive strain.

The figure on the right shows the results of compressing a conductor. Compression reduces the conductor's length and increases the cross-sectional area. As a result, the conductor's resistance decreases. This type of deformation is called compressive strain, or negative strain.
The strain gauge on your circuit board consists of a foil conductor in a zig-zag pattern mounted on a carrier tape as shown. The foil pattern terminates in solder tabs to which leads are attached for external connections. In practice the strain gauge is typically attached with a special adhesive to the surface of a solid to measure the surface strain at that point on the solid.

The previous discussion of tensile and compressive strain on conductors can apply to any solid object. However, in the case of non-conductive materials, resistance is not a factor.

Typically, the strain gauge is firmly bonded to the surface of a solid whose strain is to be measured. This allows the transducer to experience the same strain that exists at that point on the solid.

This figure shows how the strain gauge is mounted to a metal beam in the fixture on your circuit board. The orientation of the strain gauge is chosen according to the expected direction of the strain that is applied to the beam.

In this case, the beam is fixed at one end, and the force can be applied to the free end so as to deflect the beam in an up or down direction.

The strain gauge is oriented so that the longer sections of its foil pattern are parallel to the long dimension of the beam. This arrangement maximizes the compression or tension of the strain gauge with respect to the force applied to the beam.
The measurement results also depend on which surface of the solid the strain gauge is mounted. For example, this figure shows three side views of the fixture on your circuit board. In the top figure, the free end of the beam is deflected up. The top surface will experience compression, while the bottom surface is under tension. When the free end is deflected down, the tension and compression effects are reversed.

By measuring the strain that the added weight produces on the beam, you have the basics of an electronic scale.

When one or more strain gauges are mounted on a solid to measure strain in one or more directions, the device is called a load cell. The particular configuration used on your circuit board is a uniform cantilever or bending beam load cell.

The resistance change of the strain gauge throughout its range of tension and compression is relatively small.

The strain gauge on your circuit board has a nominal resistance of 120Ω. At the maximum deflection of the beam in your circuit board fixture, the resistance increases or decreases by about 0.4Ω.

Because of the strain gauge's small resistance change, it is often used with a Wheatstone bridge and amplifier circuitry to provide a usable signal. This figure is a block diagram of the strain gauge circuit on your circuit board.
The schematic symbol for the strain gauge is similar to that of a variable resistor. The symbol $\varepsilon$ (the lower-case Greek letter epsilon) indicates that the resistance is a function of strain.

The bridge output drives a current-to-voltage converter, whose output is further amplified by an op amp.

The last op amp stage has an offset adjustment to compensate for errors in the earlier stages.

NEW TERMS AND WORDS

*strain gauge* - a transducer whose resistance varies as a function of strain.

*strain* - the amount of deformation of a solid resulting from stress; expressed mathematically as the ratio of a change in an object's length to its initial unstressed reference length.

*stress* - a force acting on a solid's unit area.

*tensile strain* - strain that increases the length of a solid (also called positive strain).

*compressive strain* - strain that reduces the length of a solid (also called negative strain).

*load cell* - a device with one or more strain gauges mounted to a solid for the purpose of measuring strain in one or more directions.

*uniform cantilever* - a projecting beam that is supported at only one end and has a constant thickness along its entire length.

*bending beam load cell* - a load cell consisting of a strain gauge attached to the surface of a flexing metal beam that is fixed at one end.

*millistrain* - a unit of strain measurement equal to the ratio of 10E-3 of a length unit to the original length unit (example: milli-inches per inch).

*microstrain* - a unit of strain measurement equal to the ratio of 10E-6 of a length unit to the original length unit (example: micro-inches per inch).

*elasticity* - a property by which a solid deformed by stress returns to its original shape when the stress is removed.

*elastic limit* - the maximum amount of stress that does not cause permanent deformation of a solid.

*Hooke's law* - an equation that expresses the relationship of stress and strain ($E = \text{Stress}/\text{Strain}$).

*modulus of elasticity* - the constant of proportionality between stress and strain ($E=\text{Stress}/\text{Strain}$); measured in units of force per unit area.

*gauge factor* - the sensitivity of a resistive strain gauge; expressed mathematically as the ratio of a conductor's fractional resistance change to the fractional change in length.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
Multimeter
TRANSUDER FUNDAMENTALS circuit board
Exercise 1 – Strain Gauge Characteristics

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to explain and demonstrate the circuitry used to convert the strain gauge's small resistance change into a usable signal. You will verify your results by calibrating the circuit, adjusting the mechanical fixture, and taking resistance and voltage measurements.

DISCUSSION
• The strain gauge is part of a Wheatstone bridge.
• High precision resistors are used throughout the circuit to help minimize errors due to the strain gauge’s small resistance change.
• The strain gauge on this circuit board has a nominal resistance of 120Ω, when unstressed.
• When the strain gauge is bonded to the surface of the beam, the resistance may vary. The maximum 2% tolerance rating indicates this variation in resistance.
• The bridge outputs are connected to the inputs of op amp (U16A). The op amp is configured as a current-to-voltage converter. The equation for the U16A output voltage is:
  \[ V_O = \frac{(V \times \Delta R \times R_F)}{2R_N^2} \]
• Substituting in known constants the above equation simplifies to \[ V_O = 2.083 \times \Delta R \]
• The voltage at AMP OUT is: AMP OUT = 10.42 x \( \Delta R \)
• The op amp U16A has no offset adjustment. Potentiometer (R105) is provided to offset the amplified error voltage from the previous stage.
• To calibrate the circuit, adjust the mechanical fixture so that no stress is applied to the strain gauge.
Exercise 2 – Bending Beam Load Cell

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to explain and demonstrate the operation of a bending-beam load cell. You will verify your results by adjusting the strain gauge fixture on your circuit board, by measuring voltages, and by making calculations.

DISCUSSION
• A bending-beam load cell can be used as the basic element in electronic scales and other force measurement devices.
• Strain (ε) is defined mathematically as the ratio of the change in a solid’s length to its original unstressed length: ε = ΔL/L
  where: ΔL is the change in the solid’s length
  L is the original length of the solid
• Strain is a dimensionless; however units such as in/in are often retained to keep the perspective of this parameter.
• Since strain is a ratio, it is sometimes expressed as a percent change.
• The units millistrain (mε, or ε x 10^-3) or microstrain (µε, or ε x 10^-6) are commonly used since the solid’s change in length is very small.
• Elasticity is a property by which a solid deformed by stress returns to its original shape when the stress is removed.
• All solids have some degree of elasticity but none are perfectly elastic. There is a stress point called the elastic limit, beyond which the solid will either break or become permanently deformed.
• Strain and stress in a solid are related by an equation known as Hooke’s law:
  \[ E = \frac{\sigma}{\varepsilon} \]
  where: \( \sigma \) (the lower-case Greek letter sigma) = stress
  \( \varepsilon \) = strain
  E is a constant known as the modulus of elasticity
• The modulus of elasticity is a force per unit area and depends on the material of which the solid is composed.
• The beam on the circuit board is aluminum and has a modulus of elasticity of 10 x 10^6 pounds per square inch (psi).
• A resistive strain gauge’s sensitivity is specified by the manufacturer with a gauge factor (GF). The gauge factor is the ratio of the fractional resistance change to the fractional change in length:
  \[ GF = \frac{\Delta R/R_N}{\Delta L/L} = \frac{\Delta R/R_N}{\varepsilon} \]
• A vertical force is applied to the beam causing the beam to deflect in a vertical direction. The
deflection results in tension in the top surface of the beam, where the strain gauge is attached.
The strain caused by this stress is detected by the strain gauge, whose resistance changes in
proportion to the amount of deflection.
• The amplifier circuit can be designed to provide a meaningful readout in units such as
ounces, pounds, grams, or psi.
• The application of force is simulated by rotating the knob on the strain gauge circuit block.
The knob turns a screw which moves the guide block up or down to cause the beam to
deflect.
• The screw has a thread pitch of 28 turns per inch (tpi). The deflection of the free end of the
beam caused by rotating the knob any number of turns (n) can be calculated as follows:
\[ \Delta Y = \frac{n}{28} \]
• The following equations represent some of the design parameters of the fixture and the
circuit on this trainer. These equations can be used to calculate the output voltage resulting
from a specific number of knob rotations.
\[ \Delta Y = \frac{n}{28} \]
\[ F = \Delta Y \times 10 \]
\[ \varepsilon = F \times 1667 \]
\[ V_{\text{AMP OUT}} = 0.0025 \times \varepsilon \]
where: \( \Delta Y \) is the vertical deflection (in inches) at the free end of the beam
\( F \) is the force (in pounds) applied to the free end of the beam
\( \varepsilon \) is the strain (in microstrain) at the strain gauge
\( V_{\text{AMP OUT}} \) is the circuit output voltage (in volts).
UNIT 8 – ULTRASONIC TRANSDUCERS

UNIT OBJECTIVE
At the completion of this unit, you will be able to explain and demonstrate the principles of ultrasonic transducers and their practical application in distance measurement.

UNIT FUNDAMENTALS
Ultrasonic transducers can utilize sound waves to detect the presence of an object or to measure the distance of the object from a reference point. Applications of ultrasonic transducers include motion sensors, automatic door openers, alarm systems, proximity sensors, level controls, range finders, and fish finders.

The sound spectrum is divided into three basic ranges, as shown here. The infrasonic range consists of very low frequencies (below 20 Hz) that we generally cannot hear. Examples of infrasonic sound sources include volcanoes, earthquakes, and vibrations from heavy machinery.

The audible range includes those frequencies that can be detected by the human ear. The audible range is typically from about 20 Hz to 20 kHz, but this can vary from person to person.

Frequencies above 20 kHz are in the ultrasonic range. You cannot hear these frequencies, but they can be detected by instruments and by some animals. Bats, for example, can hear frequencies up to 100 kHz.
Familiar examples of sound transducers are the loudspeaker and the microphone. The microphone converts sound energy (voice, music, etc.) into electrical energy that can be used by an amplifier or recording device. Conversely, the speaker converts electrical signals from an amplifier into sound energy we can hear.

**Ultrasonic transmitters** and **ultrasonic receivers** are transducers that perform the same basic functions as the loudspeaker and microphone, but the sound waves are in the ultrasonic range.

There are two basic types of ultrasonic transducers: the **electrostatic transducer** and the **piezoelectric transducer**. The two types differ in their internal construction and operating characteristics, as shown in the table.

<table>
<thead>
<tr>
<th></th>
<th>Piezoelectric</th>
<th>Electrostatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transduction</td>
<td>Quartz or ceramic crystal</td>
<td>Thin metal foil</td>
</tr>
<tr>
<td>Element</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Narrow (high-Q)</td>
<td>Wide (low-Q)</td>
</tr>
<tr>
<td>Ringing</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

The devices on your circuit board are ceramic piezoelectric transducers.

This is a cross-sectional view showing the construction of a piezoelectric transducer. The basic transducer element is a **piezoelectric crystal**, which is usually composed of quartz or a synthetic material.

The crystal is sandwiched between two metal plates. The upper plate is mechanically anchored to the device's cylindrical housing, and the lower plate is attached to a vibrating diaphragm.
This figure shows that the transducer can be used as either an ultrasonic transmitter or an ultrasonic receiver, depending on how it is configured. The properties of a piezoelectric crystal are such that, when an ac voltage of ultrasonic frequency is applied (right figure), the crystal rapidly expands and contracts.

This vibration is transferred to the diaphragm, which, in turn, emits sound waves in the ultrasonic range.

Conversely, if ultrasonic sound waves from an external source were to strike the diaphragm (left figure), the resulting vibrations are imparted to the crystal. The vibration of the crystal generates an ac voltage that can be detected by an ac voltmeter or a control circuit. In this case, the transducer is configured as an ultrasonic receiver.

This figure shows how an ultrasonic transmitter and receiver pair can be used to detect the presence of an object. Ultrasonic waves from the transmitter are reflected, or echoed, off an object that lies in the path of the waves. The reflected waves are then detected by the receiver.

Ultrasonic transducers can be used to detect the presence or absence of an object in proximity sensing applications. However, it is also possible to measure the object's distance from the transducers.

The velocity of sound waves depends on the medium through which they travel. For example, if the waves are transmitted through air, you can use the speed of sound in air and measure the **transmit time** to calculate the distance to the target. Transmit time is the time that the waves take to travel from the transmitter to the target object and back to the receiver.
As with any form of radiant energy, transmitted ultrasonic waves grow weaker as they travel farther away from the transmitter.

Also, the signal is strongest in the area directly in front of the transmitter. As the angle increases outward, signal strength is attenuated. The angle in which the signal is strongest is called the angle of **directivity**.

The transducer manufacturer's data sheet often includes a directivity curve, such as the one shown here. At 0° (directly in front of the transducer), signal attenuation is 0 dB. As the angle increases, for example, to 30° left or right of center, attenuation increases to about -7.5 dB.
This figure shows the transmitter and receiver as they are positioned on your circuit board, along with their directivity patterns. Because the patterns overlap, the ultrasonic waves from the transmitter are picked up by the receiver, even without a target object.

You will see in Exercise 2 how this arrangement limits the measuring range of the transducers.

**NEW TERMS AND WORDS**

*infrasonic* - a sound frequency below the audible range (less than about 20 Hz).

*ultrasonic* - a sound frequency above the audible range (greater than 20 kHz).

*ultrasonic transmitters* - a transducer that converts electrical energy into ultrasonic sound energy.

*ultrasonic receivers* - a transducer that converts ultrasonic sound energy into electrical energy.

*electrostatic transducer* - a type of ultrasonic transducer that has a wide bandwidth, low Q, and a thin metal foil as a transduction element.

*piezoelectric transducer* - a type of transducer in which sound waves are converted to electrical signals or electrical signals are converted to sound waves.

*piezoelectric crystal* - the basic functioning element of a piezoelectric transducer.

*transmit time* - the time required for ultrasonic waves to travel from the transmitter to a target object and then to the receiver.

*directivity* - the property of an ultrasonic transducer that relates the angle of the ultrasonic waves to the signal strength.

*resonant frequency* - the frequency at which a circuit's inductive reactance and capacitive reactance are equal.

*antiresonant frequency* - the frequency at which a circuit has infinite impedance.

**EQUIPMENT REQUIRED**

F.A.C.E.T. base unit

TRANSUDER FUNDAMENTALS circuit board

Multimeter

Oscilloscope, dual trace

Ruler
NOTES
Exercise 1 – Ultrasonic Principles

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to explain and demonstrate the principles of transmission and reception of ultrasonic sound waves by using the transducers and circuitry on your circuit board. You will verify your results by observing waveform characteristics and by taking measurements with an oscilloscope.

DISCUSSION
- The ULTRASONIC TRANSDUCER circuit block contains a clock circuit which generates a 109 Hz pulse signal.
- The CLK pulse modulates a 40 kHz square wave oscillator. The output at the OSC test point is a 180 µs burst of 40 kHz pulses every 9.0 ms.
- A bandpass filter converts the OSC signal to the sine wave bursts seen at the driver (DRV) test point.
- The output of the bandpass filter drives a power amplifier stage, which boosts the signal to the transmitter.
- The resulting sine wave burst at the OUT terminal is about 10 Vpk-to-pk, and directly drives the transducer.
- One disadvantage of piezoelectric transducers is the ringing that occurs after the tone burst ends. This happens because the diaphragm continues to vibrate for a short time after the signal oscillations stop.
- The spacing of the tone bursts must be chosen to avoid interaction of adjacent bursts due to the ringing effect.
- The ultrasonic receiver boosts the signal amplitude it receives from the transmitter.
- The ringing from the transmitter is also detected by the receiver.
- The AMP output drives a DETECTOR circuit that demodulates the tone burst.
- The DETECTOR output drives a voltage comparator that inverts the pulses, squares the edges, and removes the effects of the ringing.
- The frequencies at which the impedance is resistive are the resonant frequency (f_r) and the antiresonant frequency (f_a).
- The magnitude of the transducer impedance is minimum at resonance and maximum at antiresonance.
- A transmitter should be operated at resonance to maximize mechanical to electrical efficiency.
- A receiver should be operated at antiresonance to maximize electrical to mechanical efficiency.
- For optimum sensitivity, it is common in a two-transducer system for the transmitter’s resonant frequency to match the receiver’s antiresonant frequency.
- The transducer on this circuit board has a resonant frequency of about 40 kHz.
NOTES
Exercise 2 – Distance Measurement

EXERCISE OBJECTIVE
At the completion of this exercise, you will be able to explain and demonstrate the operation of ultrasonic transducers in position sensing and range finding applications. You will verify your results with a tape measure or ruler and an oscilloscope.

DISCUSSION
• Sound waves, including those in the ultrasonic range, can travel in virtually any medium (solid, liquid, or gas).
• The velocity at which the waves travel depends on the temperature and the transmission medium.
• The most common reference for the velocity of sound in air is 331 meters per second (m/s) at 0°C. For each degree increase in temperature the velocity increases by about 0.6 m/s.
• This formula allows you to calculate the velocity at any temperature (T), in °C:
  \[ v = (331 + 0.6T) \text{ m/s} \]
• The time between the transmitted and received pulses can be measured to determine the distance of a target object from the transducer.
• Distance is the product of velocity and time (\(d = v \times t\)); using the velocity constant and the measured time, the distance between the object and the transducer can be determined.
• The arrangement of the ultrasonic transducer requires that the pulse travel an equal distance to and from the object. Therefore, the measured time is for twice the distance, or 2d. This leads to the modified equation, \(d = v \times (t/2)\), which represents the actual distance from the transducer to the object.
UNIT 9 – THE INFRARED CONTROLLER

UNIT OBJECTIVE
At the completion of this unit, you will be able to describe how infrared transducers can be used to remotely control electronic equipment. You will demonstrate infrared transmission, reception, and remote control using the INFRARED CONTROLLER circuit block on your TRANSDUCER FUNDAMENTALS circuit board.

UNIT FUNDAMENTALS

Infrared (IR) light is not actually visible light. It is another form of radiant energy that exists just above the visible red region (wavelength) in the high spectrum of electromagnetic radiation.

Besides infrared and visible light, a third type of light called ultra-violet (UV) exists just below the visible violet region of the light spectrum. Like visible light, IR light can travel through air or water. It is also commonly sent through glass or plastic fibers in a technology known as fiber optics.

The most common device used to emit IR light is a special type of LED known as an infrared-emitting diode, or IRED. The INFRARED CONTROLLER circuit block on your TRANSDUCER FUNDAMENTALS circuit board uses one of these output transducers to emit pulses of IR light. IR photons are generated by the IR emitter’s semiconductor PN junction when the junction is forward biased.
The basic sensing element for detecting IR light is a PN junction such as in diodes and transistors. Special input transducers, known as photodiodes and phototransistors, which are sensitive to the IR light, are commonly used to detect IR light.

IR photons striking the IR detector's reverse-biased PN junction cause an increase in the junction's conductivity, which in turn causes an increase in circuit current, called **photocurrent**.

Your circuit board uses a three-pin device to detect IR light. It consists of an IC that contains a photodiode, an amplifier (for current-to-voltage conversion), a Schmitt-triggered gate, an output transistor, and a voltage regulator.

IR light passes through a clear plastic lens on the detector's case and strikes the PN junction (photodiode) inside the detector.

As the incident IR light intensity increases, photocurrent increases, which causes the input voltage of the Schmitt-triggered gate to increase. When the threshold voltage of the gate is exceeded, the output of the gate goes low and turns the output transistor off. When the transistor is off, the output of the IR detector is open and can be pulled high with an external resistor to VCC.
IR emitter and detector pairs are often used to sense the presence or absence of objects that can block an IR light path. Your floppy disk drive uses this method to detect the write-protect tab on a floppy disk.

Other examples of IR applications include intrusion alarms, bar-code scanners, and smoke detectors. IR **optoelectronics** can also be used to transmit and receive voice or music by modulating the intensity (amplitude modulation) or frequency (frequency modulation) of the IR light.

An IR light source can be turned on and off to send pulses of light, which represent logical highs and lows. This method is commonly used to exchange digital data. Your circuit board uses this technique to send and receive digital codes.

Many factors affect the performance of an **IR data link**. The emitter's output power and the detector's input sensitivity for a given distance and transmission media (air for example) are crucial for reliable communications. Matching IR wavelengths and physical alignment of the two transducers are also important.
An IR data link provides wireless communication, which you can use to send instruction codes to an electronic device. This allows the device to be remotely controlled and eliminates the need for a physical connection between your transmitter and the device's receiver.

Infrared remote control can be found on most modern TVs, VCRs, stereo CD players, and many other products in the vast world of electronics. Many of these products (including your circuit board) incorporate a single IC chip on each side of the IR data link.

An **encoder** IC is used on the transmitter side of the data link to convert all control information into a coded signal. On the receiving end, a **decoder** IC is used to convert the coded signal back to control information.
NEW TERMS AND WORDS

photons - an elementary quantity (a quantum) of radiant energy.
infrared (IR) - a form of radiant energy with wavelengths between 770 nm and 1 mm, which is just below the visible light region of the electromagnetic spectrum; a type of invisible light.
ultra-violet (UV) - a form of radiant energy with wavelengths between 10 nm and 390 nm, which is just above the visible light region of the electromagnetic spectrum; a type of invisible light.
photodiodes - a light-sensitive diode whose conduction is directly related to light intensity.
phototransistors - a light-sensitive transistor whose collector current is directly related to light intensity.
photocurrent - the current produced by photons striking a semiconductor PN junction, as in a photodiode.
optoelectronics - the field of electronics that combines the use of optical and electrical energy.
data link - a communication link that allows the transfer of digital data.
encoder - a device that converts information (data) into a code.
decoder - a device that converts a code into information (data).
IRED - an LED type of output transducer that emits infrared light instead of visible light when forward biased.
radiant power - a parameter used to specify IR light power in watts (W).
radiant intensity - a parameter used to specify IR light power from a source in watts per steradian (W/sr).
steradian - a unit of measure for a solid angle.
irradiance - a parameter used to specify IR light power for given area of a surface in watts per square centimeter (W/cm²).
trinary - a base 3 system of notation, where only three different values are possible.
binary - a base 2 system of notation, where only two different values are possible.
data periods - the duration of time that is required for a unit of data to be transferred.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
TRANSDUCER FUNDAMENTALS
Oscilloscope, dual trace
Exercise 1 – IR Transmission and Reception

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to explain how infrared light can be transmitted and received, describe typical infrared transducers and their uses, and explain the importance and effect of IR power levels. You will use an oscilloscope to make observations and measurements.

DISCUSSION
- The radiation pattern of the IRED determines the physical positioning of the IR transducers.
- The IR emitter on the circuit board is an IRED that is packaged in a clear standard T 1-3/4 LED style epoxy case.
- The IRED’s junction is made of gallium arsenide (GaAs) semiconductor material which emits IR light at a peak wavelength of 940 nanometers when forward biased.
- This formula, $I_{(pk)} = (V_{CC} - V_f)/R_S$, is used to determine the IRED’s peak forward current ($I_{(pk)}$).
- The output power of an IR emitter is crucial for reliable operation of IR applications. With $I_{(pk)}$ at 91 mA, the peak radiant power of the IRED, on this circuit board, is about 15 mW. This provides a peak radiant intensity of about 14 mW/sr which drives the IR detector on the circuit board.
- The IR detector on this circuit board consists of a three-pin epoxy package that contains a photodiode and all the support circuitry required to provide a digital output.
- The internal photodiode is exposed to IR light through a clear plastic lens on the case.
- The photodiodes junction is made of silicon, which is highly sensitive to IR light with a wavelength of approximately 940 nm. This matches the wavelength of the IRED’s emitted light.
- The input sensitivity of an IR detector is also critical for proper operation of IR circuitry.
- The IR detector on this circuit board requires an irradiance of about one-half milliwatt per square centimeter (0.5 mW/cm²) to trigger the output switch.
- If the IR transducers and circuits cannot respond to the transmitted pulses of IR light fast enough, the final waveforms can become extremely distorted. This makes the response time of the IR transducer and its associated circuitry critical to the transmission and reception of reliable data.
- The amplifier and Schmitt trigger in the IR detector’s output can cause the detector’s output to be distorted. When extremely low power is fed to the IR detector, the received pulse is narrower than the transmitted pulse. When extremely high power is fed to the IR detector, the received pulse is much wider than the transmitted pulse.
Exercise 2 – IR Remote Control

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to describe how digital data is transferred via infrared light, demonstrate typical data encoding and decoding techniques used in IR remote control applications, and explain how infrared light can be used to remotely control electronic equipment. You will use an oscilloscope to make observations and measurements.

DISCUSSION
- Digital data consists of logical highs and lows that can be represented by a light source being turned on or off, respectively.
- Digital data that is transmitted via IR light can be received by an IR detector.
- The INFRARED CONTROLLER circuit block can be used to simulate the IR remote control operations of an electronic device.
- Since most digital electronic products contain microprocessors, it is often necessary to convert parallel data to serial data before transmitting the data with an IR emitter.
- The serial data received by the IR detector must be converted to parallel data before it can be used by a microprocessor.
- The encoder and decoder on the circuit board are the devices that perform the parallel-to-serial conversions.
- The encoder serially transmits nine digits of information via the IRED.
- The decoder receives the 9-digit word via the IR detector, and interprets the first five digits as an address and the last four as data.
- The encoder on your circuit board outputs trinary data and address information, which has three logic states: low, high, and open.
- By using trinary addressing on five address lines, you can address up to 243 ($3^5$) devices, whereas only 32 ($2^5$) binary addresses would be possible.
- The encoder and decoder use two consecutive pulses to represent each logic state that is needed to convey information. Two short pulses in succession represent a logical low. Two longer pulses represent a logical high, and a long pulse followed by a short pulse represents a logically open state.
- The open state is caused by an open-circuit condition (no connection) on an input line to the encoder. A low condition (0V) or high condition (15V) on any input line causes a logical low or high pattern, respectively, to occur at the encoder’s output.
- The encoder converts nine parallel input lines of information to 18 serial pulses. Two pulses form a pattern that represents each trinary digit. The nine trinary digits represent the input information and can be transmitted serially over the IR link.
The decoder recognizes this serial format and converts it back to five parallel trinary address digits and four parallel binary data bits. The decoder accepts the trinary addresses, but converts the data to binary by interpreting an open state as a logical high. The decoder recognizes the data as being valid only if two identical 9-digit words are received consecutively. The decoder's Valid Transmission (VT) signal goes high to indicate that the current data at the output is valid.

Most remote controllers transmit IR light for distances much greater than those on your circuit board. This is accomplished by setting the peak power of the IRED very high and using a common modulation technique to reduce the average power of the IRED. In this case, the encoder output modulates a higher (carrier) frequency, which in turn pulses the IRED. A modulator of this type is not needed on your circuit board since the IRED's power level is already extremely low and the data transfer rate is unaffected by this technique.

Each time you press the XMT pushbutton, the encoder outputs two identical 9-digit words, one after the other. No signal is sent between the words for a duration of 3 data periods. If XMT is still pressed after two words are sent, the encoder continues to send the same word. The output of the encoder drives a transistor that switches the IRED on and off to create pulses of IR light.

The photocurrent produced by the photodiode inside the IR detector must be converted to a voltage and amplified by a signal conditioner to produce a usable square wave for the digital input of the decoder. The IR detector's conditioned output is then fed to the decoder input. When two identical address and data patterns have been received, the data is deemed valid, the Valid Transmission (VT) signal goes high, and the decoder's 4-bit binary output is latched with the data. This updates the LED display until new valid data arrives.

If the modulation technique is used at the transmitter, the receiver must include a demodulator in the signal-conditioning circuitry to remove the high (carrier) frequency pulses.

You can determine the transferred data rate of an IR communication link in bits-per-second (bps) by taking the reciprocal of the signal's measured data period.

Digital instruction codes are commonly sent via IR light to a device to perform a task or to provide a specific function. For example, a TV may have several different codes to control the power, set the volume, and change the channels.
UNIT 10 – COMPUTER INTERFACING (OPTIONAL)

UNIT OBJECTIVE
At the completion of this unit, you will be able to explain and demonstrate the use of a computer interface to measure temperature using the IC TRANSDUCER, THERMO COUPLE, THERMISTOR, and RTD circuit blocks; control temperature using the IC TRANSDUCER circuit block; and measure force using the STRAIN GAUGE circuit block. You will verify your results with a multimeter and by loading and executing simple programs on the 32-BIT MICROPROCESSOR board.

UNIT FUNDAMENTALS

The speed, efficiency, and economy of today's microprocessors make them an ideal tool for use in the control, measurement, and processing of analog information from transducers.

Analog values from an input transducer can be digitized with an ADC (analog-to-digital converter) and transferred to the CPU via the data bus. Conversely, the CPU can write a digital value to a DAC (digital-to-analog converter) to drive an output transducer.

Many computer interface circuits involving analog signals employ a device called an analog switch. An analog switch can be turned on or off with a digital control signal, and can be used for multiplexing analog signals or for remotely configuring analog circuits.
The analog switch type used on your circuit board has three terminals: D, S, and IN. The D and S terminals are the drain and source, respectively, of the internal FET switching device.

The IN terminal is a digital input that can be either logically high or low. When IN is high, the resistance between D and S is low (typically less than 1 kΩ). When IN is low, the resistance becomes extremely high. In this condition, only a leakage current on the order of 10 picoamps (10 x 10^{-12} amp) flows between D and S.

In most cases, you can consider the path between D and S to be either a short circuit (IN = high) or an open circuit (IN = low).

The analog switch can therefore be compared to a simple mechanical switch that can be open or closed.

The analog switch ICs used on your circuit board are packaged four to a chip, as shown. Each IC has three separate power supply inputs. The +5V logic supply (V_L) is needed for the digital control input circuitry (IN1 through IN4). The + and -15V supplies are included to allow the device to switch a wide range of analog voltages.
This figure shows the locations of the three quad analog switch ICs on your circuit board.

This is a partial block diagram of the computer interface on the F.A.C.E.T. 32-BIT MICROPROCESSOR circuit board. Connector JP6 in the PARALLEL PORT circuit block contains the signals used to interface to the TRANSDUCER FUNDAMENTALS circuit board.

In addition to the DAC output and ADC input, several digital output signals are used. These are from a parallel port on the programmable peripheral interface (PPI).

This figure is a partial block diagram of the interface circuitry on the TRANSDUCER FUNDAMENTALS circuit board.
The microprocessor board can read an analog voltage from one of several circuit blocks on the transducer board. One of the functions of the analog switches is to select the circuit block whose output is to be read. The outputs from several of the circuit blocks are each connected to the S terminal of an analog switch. The D terminals are tied together and connected to ADC IN.

The control input of each analog switch is connected to a separate bit from output port B (PB0 -PB4). The code that the CPU outputs on port B determines which circuit block is selected. For example, if the CPU were to output 02H (PB1 high, all other bits low), the CPU would read the THERMISTOR circuit block output via the ADC IN line.

Note that only one bit at a time on port B can be high. Otherwise, more than one analog signal would be connected to ADC IN, and the conflicting signals would result in a measurement error.

The output level of some circuit blocks must be amplified by the instrumentation amplifier before being read via the ADC IN line. Additional analog switches are used to select which circuit block outputs are connected to the instrumentation amplifier. Three analog switches from U6 select a signal to drive the non-inverting input. Three analog switches from U2 select a signal to drive the inverting input.

Additional circuit boards in the F.A.C.E.T. program are available for further experiments in computer interfacing with the 32-BIT MICROPROCESSOR board.

With the MICROPROCESSOR APPLICATION board, you can demonstrate open and closed-loop temperature control using an IC temperature transducer. You can also control the speed, direction, and on/off function of a small dc motor.
With the MOTORS, GENERATORS, and CONTROLS circuit board, you can use the microprocessor board to control the number of steps and the direction of rotation of a stepper motor.

NEW TERMS AND WORDS
None

EQUIPMENT REQUIRED
F.A.C.E.T. base unit
TRANSCLUDER FUNDAMENTALS circuit board
32-BIT MICROPROCESSOR circuit board
Multimeter
AC Adapter 9 Vdc @0.5A (QG91730)
20-Pin Ribbon Cable Assembly (KJ91627)
**Exercise 1 – Temperature Control/Measurement**

**EXERCISE OBJECTIVE**
When you have completed this exercise, you will be able to explain and demonstrate temperature control and measurement using a computer interface. You will verify your results with a voltmeter and by loading and executing simple programs on the 32-BIT MICROPROCESSOR circuit board.

**DISCUSSION**
- Four output bits from the PPI (PB0- PB3) drive a block select circuit, which consists of analog switches.
- Depending on the port B output code, one temperature transducer block is selected to send its output to the CPU via the ADC IN line allowing the CPU to read the temperature of the oven using any of the four transducers.
- The TEMP header in the IC TRANSDUCER circuit block has four shunt-selectable set points, and a fifth position labeled COMP (computer). When the shunt is in the COMP position, the set point is determined by a value sent by the CPU via the DAC OUT line.
- The analog switch driven by PB0 switches the IC TRANSDUCER output to ADC IN.
- When the microprocessor outputs 02H on port B (PB1 high), three analog switches are enabled. The two other analog switches (U6A and U2A) direct the +OUT and -OUT voltages from the THERMISTOR circuit block to the + and - inputs of the instrumentation amplifier.
- The computer interface to the RTD circuit block is similar to that of the THERMISTOR block. However, since the RTD block has a unipolar output, only one analog switch connects the block output to the instrumentation amplifier. Another analog switch grounds the inverting input of the amplifier for the proper bias.
- When the THERMOCOUPLE block is selected, its + and - outputs are directed to the instrumentation amplifier inputs. Because the low-level thermocouple output needs additional amplification, the IA OUT voltage is connected to the op amp located in the THERMOCOUPLE circuit block. The op amp output is directed to the ADC IN line via analog switch U8D.
Exercise 2 – Force Measurement

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to explain and demonstrate how a microprocessor interface can be used to measure force. You will verify your results by using a multimeter and the STRAIN GAUGE circuit block on the TRANSDUCER FUNDAMENTALS circuit board.

DISCUSSION
• The analog output from a strain gauge circuit can easily be digitized by an ADC for measurement and processing by a computer.
• The microprocessor can scale the analog value into various force units (pounds, ounces, grams, kilograms, psi, etc.).
• The output voltage of a bending beam load cell is also a function of the beam's deflection, therefore this reading could also be scaled in units of displacement (inches, millimeters, etc.).
• The scaling can be done in software rather than using additional external circuitry at additional cost.
• The analog switch that directs the STRAIN GAUGE circuit block output to the ADCIN line is controlled by PB4.
• When maximum tensile strain is applied to the end of the beam, the voltage has a maximum positive value. The resulting ADC OUT hex value is also maximum (FFH).
• When maximum compressive strain is applied, the voltage has a maximum negative value. The ADC OUT hex value is minimum (00H).
• When the beam is unstressed, the strain gauge circuit output is about 0V, and ADC OUT has a mid-scale value of 80H.
• Because the STRAIN GAUGE circuit block outputs both positive and negative voltages, the ADC must be set for bipolar operation.
• An analog voltage measurement can be calculated from the digitized value that is output from the ADC.
• In the bipolar mode of operation, the ADC has a 10V input range (-5V to +5V) and an 8-bit output. The resolution is therefore 39.06 mV (10V ÷ 256 steps).
• The voltage is calculated by first subtracting 128 from the decimal value to account for the bipolar offset. Then multiply by the resolution as follows.
  \[ V = (\text{decimal value} - 128) \times 39.06 \text{ mV} \]
APPENDIX A – SAFETY

Safety is everyone’s responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch “live” wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.