Chapter 2

Sensors & Actuators

2.1   Problems

Problem 2.1 (Music icon address) *What screen-row-column address would the controller assign to the music icon shown in Figure 2.10 if the icon is located on the third screen of 16 possible screens?*

(ans: Sixteen screens have 4-bit addresses from 0000 (first screen) to 1111 (sixteenth screen). The third screen has address 0010, giving the music icon the screen-row-column address 0010-10-01.
)

Problem 2.2 (Calculator switch array) *A scientific calculator has 50 keys for digits and logarithmic and trigonometric functions arranged in five rows and ten columns. Specify a binary address code to indicate what key was pressed.*

(ans: Five rows require a 3-bit code and ten columns a 4-bit code. Hence, each key has a 7 bit address.
)

Problem 2.3 (Forming a touch screen switch array) *A touch screen array has a count of rows and columns that sums to 10. What is the structure of the array that accommodates the maximum number of keys?*

(ans: Five rows and five columns accommodate 25 switch locations.
)

Problem 2.4 (Finger swipe along a switch array) *Extending Example 2.7, a linear switch array is 10 cm long and has a resolution $R_s = 2$ switches/mm. A swipe motion is detected if the mid-point changes by more than 8 switches. If the sampling period $T_s = 0.1$ s, what is the minimum finger swipe speed along the linear array that indicates a swipe motion?*

(ans: $\delta x_m = 8$ switches, $R_s = 2$ switches/mm, and $T_s = 0.1$ s, gives

$$v_{min} = \frac{\delta x_m}{R_s\, T_s} = \frac{8\,switches}{2\,switches/mm \times 0.1\,s} = 40\,mm/s$$

)

Problem 2.5 (Multiple finger gesture) *Extending Example 2.8, a linear switch array is 10 cm long and has a resolution $R_s = 2$ switches/mm, and sampling period $T_s = 0.1$ s. If $P1 = 20$ and $P2 = 40$ and $P1' = 22$ and $P2' = 36$ is sensed as a gesture, what is the finger swipe speed? Is it widening or spreading?*

(ans:

$$S = P2 - P1 = 40 - 20 = 20$$

$$\frac{S}{R_s} = \frac{20 \, switches}{2 \, switches/mm} = 10 \, mm$$

$$S' = P2' - P1' = 36 - 22 = 14$$

$$\frac{S'}{R_s} = \frac{14 \, switches}{2 \, switches/mm} = 7 \, mm$$

Hence, the finger separation narrows. The widening separation speed is

$$v_F = \frac{S'/R_s - S/R_s}{T_s} = \frac{7 \, mm - 10 \, mm}{0.1 \, s} = -30 \, mm/s$$

Equivalently, the finger narrowing separation speed is 30 mm/s.
)

Problem 2.6 (Number of bits in a large color LED display) *A large color billboard is a two-dimensional array of $2^{10} \times 2^{10}$ pixels, with each pixel containing red, green and blue LEDs. (Single LED packages contain separate R, G, and B LEDs inside.) Assuming that each LED is controlled to shine at one of 256 levels, how many bits are needed to specify a color image on the billboard? How many different colors can each 3-LED pixel display?*

(ans: Number of LEDs is

$$2^{10} \times 2^{10} \times 3 = 3 \times 2^{20} \, (\approx \; 3 \; million)$$

256 levels are set by 8 bits ($= 2^3$), so the total number of bits per image equals 3×2^{23}, or 24 million bits. The number of colors that each 3-LED pixel can display equals

$$2^{24} = 2^4 \times 2^{20} = 16 \times 10^6 \; (\; 16 \; million \; colors)$$

)

Problem 2.7 (Number of possible images in a large color LED display) *A large color billboard is a two-dimensional array of $2^{10} \times 2^{10}$ pixels, with each pixel containing red, green and blue LEDs. Assuming that each LED is controlled to shine at one of 256 levels, what is the number of different images that can be displayed? Express answer as a power of 10.*

(ans: The number of colors each RGB pixel can display equals 16×10^6. The number of different possible images that 10^6 pixels can display is

$$16 \times 10^6 \times 10^6 = 16 \times 10^{12}$$

or 16 trillion images.
)

Problem 2.8 (Bit rate to generate a full-screen movie) *A video game displays images on your laptop monitor having a resolution of* 1680×1050 *pixels. Each pixel contains a red, green, and blue LEDs, and each LED is controlled to shine at one of 256 levels. The game produces a new image on the screen 60 times per second. How many bits per second are being sent to your monitor while you are playing your game? Give answer in scientific notation* ($x.xx \times 10^y$).

(ans: Number of LEDs equals

$$1,680 \times 1,050 \times 3 = 5.20 \times 10^6 \text{ LEDs/frame}$$

256 levels per LED are set by 8 bits, so the total number of bits per frame equals

$$8 \text{ bits/LED } \times 5.20 \times 10^6 \text{ LEDs/frame} = 4.16 \times 10^7 \text{ bits/frame}$$

At 60 frames per second, the bit rate equals

$$60 \text{ frames/s} \times 4.16 \times 10^7 \text{ bits/frame} = 2.50 \times 10^9 \text{ bits/s}$$

)

Problem 2.9 (Smartphone location from two range measurements) *This problem considers the location information using the range values measured by two antennas. Let antennas* $A1$ *and* $A2$ *be located 5 km apart. Determine the two possible locations for the smartphone relative to antenna* $A1$ *when the smartphone range from* $A1$ *is 3 km and from* $A2$ *is 3.5 km.*

(ans: Let $A1$ *be at (0,0), and* $A2$ *at (5,0) km. Smartphone location is* (x_S, y_S). *Then,* $A1$ *range value* $R_1 = 3$ *gives*

$$x_S^2 + y_S^2 = 9$$

$A2$ range value $R_2 = 3.5$ *gives*

$$(x_S - 5)^2 + y_S^2 = 12.25$$

Equating both to y_S^2 *gives*

$$y_S^2 = 9 - x_S^2 = 12.25 - (x_S - 5)^2 \quad [= 12.25 - (x_S^2 - 10x_S + 25)]$$

Canceling x_S^2 *and solving for* x_S *yields*

$$x_S = \frac{9 - 12.25 + 25}{10} = 2.175 \, km$$

The two solutions for y_S *come from the* $A1$ *equation*

$$y_S = \pm\sqrt{9 - x_S^2} = \pm\sqrt{9 - 4.730625} = \pm\sqrt{4.269375} = \pm 2.066 \, km$$

)

Problem 2.10 (Smartphone location region caused by range errors) *Sketch and determine the four points defining the region that contains your smartphone when the range measured from antenna $A1$ is (3 ± 0.1) km and that from $A2$ is (3.5 ± 0.1) km.*

(ans: Let $A1$ be at (0,0), and $A2$ at (5,0) km. Smartphone location is (x_S, y_S).
  Consider solutions due to positive $(+)$ and negative $(-)$ errors with the fours cases $(++), (+-), (-+), (--)$.
  First $(++)$, $A1$ range value $R_1 = 3.1$ and $A2$ range value $R_2 = 3.6$ give

$$x_{S++} = \frac{9.61 - 12.96 + 25}{10} = 2.17 \, km$$

The two solutions for y_S come from the $A1$ equation

$$y_{S++} = \pm\sqrt{9.61 - 2.17^2} = \pm 2.22 \, km$$

For $(+-)$, $A1$ range value $R_1 = 3.1$ and $A2$ range value $R_2 = 3.4$ give

$$x_{S+-} = \frac{9.61 - 11.56 + 25}{10} = 2.31 \, km$$

The two solutions for y_S come from the $A1$ equation

$$y_{S+-} = \pm\sqrt{9.61 - 2.31^2} = \pm 2.07 \, km$$

For $(-+)$, $A1$ range value $R_1 = 2.9$ and $A2$ range value $R_2 = 3.6$ give

$$x_{S-+} = \frac{8.41 - 12.96 + 25}{10} = 2.05 \, km$$

The two solutions for y_S come from the $A1$ equation

$$y_{S-+} = \pm\sqrt{8.41 - 2.05^2} = \pm 2.06 \, km$$

For $(--)$, $A1$ range value $R_1 = 2.9$ and $A2$ range value $R_2 = 3.4$ give

$$x_{S--} = \frac{8.41 - 11.56 + 25}{10} = 2.19 \, km$$

The two solutions for y_S come from the $A1$ equation

$$y_{S--} = \pm\sqrt{8.41 - 2.19^2} = \pm 1.91 \, km$$

)

Problem 2.11 (Pulse time for a bar code scan) *In Example 2.21, if a laser spot moves across the bar code at 10 m/s, and the width of the thinnest bar is 1 mm, what is the duration of the shortest pulse produced by the scanner? Give answer in μs $(10^{-6}$ s).*

(ans:

$$t = \frac{d}{v} = \frac{10^{-3} \, m}{10 \, m/s} = 10^{-4} \, s = 100 \, \mu s$$

)

Problem 2.12 (IR range sensor) *In an IR autofocus camera, the emitter and detector are separated by* 1 *cm and positioned* 1 *cm behind the lenses, which are modeled as pinholes. The light reflected from an object produces a spot* 1 *mm from the centerline of the detector pinhole. What is the range of the object from the camera in meters (m)?*

(ans: With $s = 10^{-2}\,m$, $f = 10^{-2}\,m$, $x = 10^{-3}\,m$ gives

$$r = \frac{sf}{x} = \frac{10^{-2}\,m \times 10^{-2}\,m}{10^{-3}\,m} = 0.10\,m$$

)

Problem 2.13 (Digital IR range sensor) *In a digital IR autofocus camera, the emitter and detector are* 1 *cm apart and the detector array is* 1 *cm behind the lens. An IR detector element has near and far limits* $x_F = 0.01\,mm$ *and* $x_N = 0.02\,mm$ *that senses light reflected from an object located from* r_N *to* r_F *in range. Determine the values of* r_N *and* r_F *in m.*

(ans:$s = 10^{-2}\,m$, $f = 10^{-2}\,m$, $x_F = 10^{-5}\,m$ gives

$$r_F = \frac{sf}{x_F} = \frac{10^{-2}\,m \times 10^{-2}\,m}{10^{-5}\,m} = 10\,m$$

$s = 10^{-2}\,m$, $f = 10^{-2}\,m$, $x_N = 2 \times 10^{-5}\,m$ gives

$$r_N = \frac{sf}{x_F} = \frac{10^{-2}\,m \times 10^{-2}\,m}{2 \times 10^{-5}\,m} = 5\,m$$

)

Problem 2.14 (Digital IR range sensor dimensions) *In a digital IR autofocus camera, the emitter and detector are* 1 *cm apart and the detector array is* 1 *cm behind the lens. What are the detector element's near and far limits* (x_F *and* x_N) *that senses light reflected from an object located* 1 *m to* 4 *m away? Give answer in millimeters (mm).*

(ans:$s = 10^{-2}\,m$, $f = 10^{-2}\,m$, $r_F = 4\,m$ gives

$$x_F = \frac{sf}{r_F} = \frac{10^{-2}\,m \times 10^{-2}\,m}{4\,m} = 0.25 \times 10^{-4}\,m = 0.025 \times 10^{-3}\,m = 0.025\,mm$$

$s = 10^{-2}\,m$, $f = 10^{-2}\,m$, $r_N = 1\,m$ gives

$$x_N = \frac{sf}{r_N} = \frac{10^{-2}\,m \times 10^{-2}\,m}{1\,m} = 10^{-4}\,m = 0.1 \times 10^{-3}\,m = 0.1\,mm$$

)

Problem 2.15 (Sonar ranging - range to TOF) *A sonar system operates in air up to a maximum range of 4 m. What is the maximum TOF? Give answer in ms (10^{-3} s)?*

(ans: c = 343 m/s gives

$$TOF_{max} = \frac{2r_{max}}{c} = \frac{8\,m}{343\,m/s} = 0.023\,s = 23\,ms$$

)

Problem 2.16 (Sonar ranging - TOF to range) *A sonar system observes a $TOF = 10\,ms$. What is the object range in meters (m)?*

(ans: c = 343 m/s gives

$$d = \frac{c \times TOF}{2} = \frac{343\,m/s \times 10^{-2}\,s}{2} = 1.72\,m$$

)

Problem 2.17 (Sonar ranging resolution) *A sonar system experiences a jitter in the echo arrival time because of dynamic temperature variations in air, which limits the TOF resolution to $\Delta TOF = \pm 50\mu s$. What is the corresponding sonar range resolution Δr in mm?*

(ans: c = 343 m/s gives

$$\Delta d = \frac{c \times \Delta TOF}{2} = \frac{343\,m/s \times \pm 5 \times 10^{-5}\,s}{2} = \pm 858 \times 10^{-5}\,m = 8.58\,mm$$

)

Problem 2.18 (Radar ranging - range to TOF) *A radar system operates up to a maximum range of 100 m. What is the maximum TOF?*

(ans: $c = 3 \times 10^8$ m/s gives

$$TOF_{max} = \frac{2r_{max}}{c} = \frac{200\,m}{3 \times 10^8\,m/s} = 66.7 \times 10^{-8}\,s = 0.667\,\mu s$$

)

Problem 2.19 (Radar ranging - TOF to range) *A radar system observes a $TOF = 0.1\,\mu s$. What is the object range in meters (m)?*

(ans: $c = 3 \times 10^8$ m/s gives

$$r = \frac{c \times TOF}{2} = \frac{3 \times 10^8\,m/s \times 10^{-7}\,s}{2} = 15\,m$$

)

Problem 2.20 (Radar ranging resolution) *A radar system is specified to have a range resolution of* $\pm 0.1m$. *What is the corresponding resolution in the radar TOF?*

(ans: $c = 3 \times 10^8$ *m/s gives*

$$\Delta TOF = \frac{2\Delta r}{c} = \frac{\pm 2 \times 10^{-1}\, m}{3 \times 10^8\, m/s} = \pm 0.67 \times 10^{-9}\, s = \pm 6.7 \times 10^{-10}\, s \ \ (\pm 0.67\, ns)$$

)

2.2   Excel Projects

Project 2.1 (Implementing a counter) *Modify Example 13.10 to place the count in cell A2. Replace the rectangles with your favorite shape.*

(ans: On the PC: Access the Macros *icon in the* View *tab on the Excel ribbon, and select* Macros, *and then* Edit *to open the Macro programs.*
On the Mac: Access the Editor *icon in the* Developer*to open the Macro programs.*
The Macro program appears as

```
Sub counter()
' counts the number of times shape is clicked
Range("A1").Value = Range("A1").Value + 1   ' increments A1
End Sub
Sub reset()
' resets the counter to 0
Range("A1").Value = 0     ' set A1=0
End Sub
```

Change "A1" to "A2" - three times - in the program to change the location of the counter cell. (Change A1 to A2 in the comment as well.)
The simplest method of change shapes is to delete the old cells, insert new ones, and then assign Macros to the new shapes.
)

Project 2.2 (Implementing a 2×4 **switch array)** *Extend Example 13.11 to implement a switch array having two rows and four columns. Provide the binary addresses of the row and column location with each bit in a separate cell.*

(ans: Starting with Example 13.11, insert two columns by right-clicking on column heading "C" and selecting Insert *twice. Insert four additional* nameable *shapes, such as times, arrow, triangle, and diamond. Compose a Macro that writes the decimal address of the row (0-1) and of the column (0-3) in the original cells,* E2 *for Rows and* E3 *for columns. When two columns are added, the Column address contains two bits, and the Row and Column address cells appear in* G2 *for the Row and* G3 *for the Column. In* G2 *insert the Excel command*

$$=E2$$

because the decimal number is the same as the binary value. Express the Column decimal number as a Column 2-bit address in G3 *with*

$$=DEC2BIN(E3,2)$$

	A	B	C	D	E	F	G
1						Address:	
2					1	Row=	1
3					2	Column=	10
4							
5							

	E	F	G
1		Address:	
2	1	Row=	=E2
3	2	Column=	=DEC2BIN(E3,2)

```
Sub square()
Range("E2").Value = 0
Range("E3").Value = 0
End Sub
--------------------
Sub star()
Range("E2").Value = 0
Range("E3").Value = 1
End Sub
--------------------
Sub smiley()
Range("E2").Value = 1
Range("E3").Value = 0
End Sub
--------------------
Sub heart()
Range("E2").Value = 1
Range("E3").Value = 1
End Sub
--------------------
Sub X()
Range("E2").Value = 0
Range("E3").Value = 2
End Sub
--------------------
Sub arrow()
Range("E2").Value = 0
Range("E3").Value = 3
End Sub
--------------------
Sub triangle()
Range("E2").Value = 1
Range("E3").Value = 2
End Sub
--------------------
Sub diamond()
Range("E2").Value = 1
Range("E3").Value = 3
End Sub
```

)

Project 2.3 (Specifying your favorite cell colour) *Example 13.12 shows the VBA Macro that increases and decreases the red component of a cell color. Complete the worksheet by writing the VBA code that also specifies the green and blue components.*

(ans: The VBA Macro `CellColor` *sets the RGB color of the cells within* `A1:B3` *and is called by the other Macros. The other Macros keep values within limits and are assigned to the shapes that increase and decrease the red, green, and blue components.*

	A	B	C	D	E	F
1			R=	157	^	v
2			G=	77	^	v
3			B=	117	^	v

```
Sub CellColor()
    Range("A1:B3").Interior.Color = RGB(Range("D1").Value,
        Range("D2").Value, Range("D3").Value)
End Sub
--------------------
Sub More_R()
If Range("D1").Value < 245 Then
    Range("D1").Value = Range("D1").Value + 10
End If
CellColor
End Sub
--------------------
Sub Less_R()
If Range("D1").Value > 10 Then
    Range("D1").Value = Range("D1").Value - 10
End If
CellColor
End Sub
--------------------
Sub More_G()
If Range("D2").Value < 245 Then
    Range("D2").Value = Range("D2").Value + 10
End If
CellColor
End Sub
--------------------
Sub Less_G()
If Range("D2").Value > 10 Then
    Range("D2").Value = Range("D2").Value - 10
End If
CellColor
End Sub
--------------------
Sub More_B()
If Range("D3").Value < 245 Then
    Range("D3").Value = Range("D3").Value + 10
End If
CellColor
End Sub
--------------------
Sub Less_B()
If Range("D3").Value > 10 Then
    Range("D3").Value = Range("D3").Value - 10
End If
CellColor
End Sub
```

)

Project 2.4 (Color display specifications) *Compose a worksheet that specifies a color RGB display with each LED having 256 levels having values n_{row} (number of rows), n_{col} (number of columns), and f_{frame} (frame rate with units frames/second) and computes n_{pixels} (number of pixels), n_{LED} (number of LEDs), n_B (number of bytes per frame), n_b (number of bits per frame), and $\mathcal{D}$ (data rate in bits/second).*

(ans: The parameter names were entered using the Font/Subscript *option, cell outlines and color fill for emphasis. The parameter values were entered into Column* B *and the resulting computed values were displayed in Column E. Macros are not needed.*

	A	B	C	D	E
1	n_{row} =	480		n_{pixel} =	307200
2	n_{col} =	640		n_{LED} =	921600
3	f_{frame} =	30		n_B =	921600
4				n_b =	7372800
5				D=	221184000

	A	B	C	D	E
1	n_{row} =	480		n_{pixel} =	=B1*B2
2	n_{col} =	640		n_{LED} =	=3*E1
3	f_{frame} =	30		n_B =	=E2
4				n_b =	=8*E3
5				D=	=E4*B3

)