Sensors and Actuators

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***Abstract*—Sensors are devices that detect and measure data from the physical world including but not limited to temperature, light, motion, pressure, and acceleration. Which are converted to electric signals that must go through signal conditioning prior to being processed by control systems. Actuators on the other hand, are devices who perform the opposite by transforming electric signals into physical attributes such as displacement, force, or motion. Together, they form the basic components in embedded systems, they work hand in hand to automating and controlling these interactions in many engineering applications. This report presents an analysis of functional sensors and actuators in embedded systems, focusing on operating principles, interfaces, and comparisons between sensors and actuators of different models, followed by the case study of a real-world application through an HVAC system.**

Keywords--- Sensors, Actuators, Embedded Systems, Signal Conditioning, Control Systems, HVAC System.

I. INTRODUCTION

Designing embedded systems is fundamentally an exercise in managing interaction with the physical world. While processing units execute algorithms and make decisions, the precision of those orders is tied to how the physical quantities are sensed as well as how consequent control actions are applied. As a result, integration of suitable sensors and actuators often play a more critical role to the system's performance compared to the computational platform itself.

In practice, embedded systems employ various sensing technologies alongside actuation mechanisms. Considering sensors and actuators each adopt their own interfacing method as well as requiring specific signal conditioning and processing algorithms. These factors need to be considered when integrating all components within an embedded system to ensure righteous functionality and accuracy.

Sectioned into three main parts, the report firstly analyses sensors across several manufacturers and families, highlighting key specifications of each. Secondly, it inspects actuators focusing on different driving methods, safety considerations, and control implications. Finally, these concepts are brought together through an illustrative HVAC case study showcasing how sensor and actuator selection directly impacts the reliability of real-world embedded systems.

II. SENSORS

A. Temperature Sensor

Temperature sensors are instruments used to measure the temperature of an object or an environment. Commonly used in various applications such as thermometers, refrigerators, water heaters, and air-conditioners. There are different types of temperature sensors such as: Thermocouples, Resistance Temperature Detectors (RTDs), Thermistors etc [1].

Regardless of the type, they all revolve around measuring a physical property as a function of temperature, the main difference being the physical quantity itself and the representation of it (analogue or digital). For instance, RTDs measure the linear change of resistance with temperature while thermocouples use dissimilar metals joined at an end to generate a voltage proportional to the difference in temperature between the ends. Sensors are then calibrated to traditional temperature scales in relation to a standard such as the boiling point of water at known pressure [2].

1. LM35

The LM35 series are precision integrated-circuit contact temperature sensors. They operate by outputting a voltage of linear proportionality to the Centigrade temperature relying on a temperature-dependent semiconductor junction behaviour. This analogue output is the only functional mode of the LM35. For the most part, the signal outputted requires no external amplification as it can be connected to most Analog to Digital Converter (ADC) inputs, hence amplification is optional. In addition, due to the linearity, LM35 need no external calibration, trimming, or a linearization algorithm of any sort providing typical accuracies of ±0.25 ˚ at room temperature and ±0.75 ˚at a range of -55˚ to 150˚. However, a controller would require an ADC to interpret the analogue signal outputted by the sensor. Moreover, an external conversion algorithm is mandatory to obtain a temperature reading from the output voltage, the equation (1) below showcases the conversion of voltage output to the corresponding temperature reading [3].

$$V_{out}/10 = \text{Temperature} \quad (1)$$

2. MLX90614

The MLX90614 is a contactless Infra-Red (IR) thermometer, it detects IR radiation using a thermal sensing element, a thermopile, converting this thermal energy into a small voltage. Contrary to the LM35, this model includes an internal low-noise amplifier, it also accommodates a built-in 17-bit ADC converting the amplified voltage signal into a computer comprehensible digital format. It supports a I²C-compatible protocol via SMBus as its digital interface. Furthermore, temperature calculation is executed internally using a powerful digital signal processor. Operating at an ambient temperature (Ta) range of -40˚C - 125˚C and an object temperature (To) range of -70˚C - 380˚C. The MLX90614 provides an accuracy of 0.5˚C. It is also factory calibrated hence needing no external calibration just like the LM35 [4].

TABLE I. SUMMARY TEMPERATURE SENSORS' SPECIFICATIONS

comparison	**Temperature Sensors**	
	LM35	***MLX90614***
Type	Semiconductor IC	Infrared thermopile
Interface to controller	Analogue	SMBus
Connection	Contact	Contactless
Range	-55˚C - 150˚C	Ambient: -40˚C - 125˚C Object: -70˚C - 380˚C
Noise	Susceptible to electric noise	Less electrical noise sensitivity higher optical/thermal disturbances
Resolution	Depends on external ADC	0.02˚C

B. *Light Sensors*

Light sensors are devices that detect light converting it into electrical signals such as voltage, current, or even changes in resistance. Common types include photoresistors like the GL5528 model, and photodiodes such as the BH1750FVI to be discussed ahead [5].

1. *GL5528*

The Gl5528 is a passive photoresistor light sensor which refers to a resistor that varies depending on the luminance variation. Consequently its resistance is excited by an external voltage or current to make use of the resistance alteration. Moreover, it operate over a broad range of illuminance namely 10Lux – 100Lux yet it is not factory calibrated. Finally, the max external voltage and power are 150V and 100W respectively alongside maximum sensitivity of 540 nm [6].

2. *BH1750FVI*

BH1750FVI is an active digital Ambien Light sensor compatible with both IC and I²C bus interfaces. It converts illuminance to a 16-bit digital signal through an internal ADC. It allows for high resolution detection at a range of 1lux to 65535lux. In addition, it provides typical accuracy of ±20% for small reading at mode dependent resolutions of 0.5lux / 1lux/ 4lux as well as rejecting 50Hz to 60Hz noise with infrared having minimal influence on measurements. Finally, this model is at peak sensitivity around 560 nm with a human like response [7].

TABLE II. SUMMARY LIGHT SENSORS' SPECIFICATIONS

Comparison	**Light Sensors**	
	GL5528	***BH1750FVI***
Classification	Passive	Active
Output type	Variable resistance	16-bit Digital
Signal conditioning	External	Internal
Spectral peak	540nm	560nm

C. *Distance Sensors*

Distance sensors measure the space between themselves and an object, they are used in numerous industries for tasks like positioning and automation. The main types of distance sensors include ultrasonic, infrared, laser, Time-of-Flight (ToF), radar, and LIDAR [8]. Generally, the mechanism followed by most types is emitting a signal, having it reflect off a surface and received again by the sensor. By measuring its runtime, the distance can be calculated using the time measured as well as known parameters such as the speed of signal emitted [9].

1. *GP2Y0A51SK0F*

GP2Y0A51SK0F is a distance measuring sensor unit, composed of an integrated combination of position sensitive detector (PSD), infrared emitting diode IR-LED, and signal processing circuit. It outputs an analogue signal represented using voltage to represent the respective distance, where higher voltage resembles closer distance. It reliably measures distances within a 2 cm to 15 cm range at timing rate of 16.5ms using the triangulation method and an operating temperature of -10˚C to 60˚C [10].

Accuracy of this sensor is not specified quantitatively by the datasheet, instead it provides non-linear voltage-to-distance characteristic. Hence an external algorithm is required to convert voltage with the respective temperature, as well as an external ADC to digitize and process obtained signal [10].

2. *VL53L0X*

VL53L0X is an optical ToF distance sensor. It integrates a single-photon avalanche diode array, a laser emitter, and an embedded microcontroller. It uses a digital I²C interface (up to 400 kHz), where communication is via a two-wire serial bus. However, the host must actively control the sensor, as interaction is command-based not passive reading also this sensor needs a minimum timing of 20 ms. The distance is computed internally within the sensor itself and sent over I²C directly in millimeters either by polling or interrupt.

The device offers a much wider range of reading compared to the GP2 model up to 2m, with a typical ranging accuracy of ±3% given as a percentage of the measured distance resulting in a condition-dependent accuracy nature as well as a resolution as low as 1 millimeter [11].

TABLE III. SUMMARY DISTANCE SENSORS' SPECIFICATIONS

Comparison	**Distance Sensors**	
	GP2Y0A51SK0F	***VL53L0X***
Type	Optical triangulation	Optical time-of-flight
Interface	Analog voltage	Digital (I²C)
Range	2cm – 15cm	Up to 2m
Timing rate	Measuring cycle 16.5ms	Programmable timing budget min = 20ms

D. *Motion Sensors*

Motion sensors are electronic devices designed to detect and measure movement. They are mainly implemented in security systems but can also be found in phones, paper towel dispensers, game consoles, and virtual reality systems [12].

Contrary to handheld and isolated sensors, motion sensors are typically embedded systems containing a sensor unit being the core component for detecting changes in the environment, an embedded computer being the processing unit which analyses signals received from sensors, and hardware being the mechanical component [12].

Motion sensors are split into two main types, passive and active. The difference between both is a transmitter found only in an active motion sensor. In other words, passive ones such as Panasonic's EKMC1601112 detect motion based on perceived increase of radiation in its environment, while active sensors such as the BGT60TR13C measure the changes in the transmitted signal and its reflection into the receiver to perceive motion [12].

1. *EKMC*

The EKMC1601112 is a passive pyroelectric infrared sensor that relies on the variations in infrared rays to detect motion. It measures corresponding thermal energies where the difference between target and background is at least 4°C. Using a multi lens, the radiation is sensed and passed to a Quad type passive infrared (PIR) element containing an amplifier circuit. In addition to a comparator output circuit resembling detection as a voltage high output while no detection results in a voltage low output [13].

Depending on the lens type, the EKMC series offers a standard 5m detection distance type as well as a long distance 12m detection type, in addition to a 94° × 82° and 102° × 92° (Horizontal × Vertical) detection angle ranges respectively. Furthermore, great electromagnetic shielding capability is provided by the metal packaging concealing the entire circuitry. However, noise external noise reduction is advised as power supply noise can cause operating errors [13].

2. *BGT60TR13C*

BGT60TR13C is an active radar-based sensor. It operates by transmitting a 60 GHz frequency modulated continuous wave signal and receiving its echo using three receiving channels. The reflected signals are measured at a range of 58.0 GHz to 63.5 GHz. It compares the values to identify a frequency and/or phase change. Contrary to the Panasonic EKMC, this model consists of three ADC channels each of 12 bits resolution with a sampling rate of up to 4 MSps. However, just like the EKMC, the signal requires amplification which is also executed internally using a voltage gain amplifier in addition to a high pass filter. Since this model does not output a binary motion/no motion signal, it handles reflected signals providing samples intermediate frequency radar samples which are digitized and stored in an on-chip FIFO after which they are read out via a digital interface (SPI) [14].

The BGT60TR13C's three receiving channels allow for spatial resolution support. With a detection range depending on the 5.5 GHz bandwidth of reception, the BGT operates at a 201 mA supply current this poses a high consumption power compared to the EKMC's tiny 170 µA. However, it prioritises robust detection, range, and resolution by outputting more meaning full signals rather than a motion/no motion output. Therefore, an angle-of-arrival estimation as well as information about velocity can be extracted from the sampled IF signals [14].

TABLE IV. SUMMARY MOTION SENSORS' SPECIFICATIONS

Comparison	Motion Sensors	
	EKMC	***BGT60TR13C***
Sensor type	Passive Infrared	Active radar
Output type	Digital comparator output	Digitized IF radar samples
Internal buffer	None	FIFO buffer
Conditioning	On-chip amplifier and comparator	On-chip filters, amplifiers, and ADC
Processing location	On-sensor decision	External MCU

E. Pressure Sensors

Pressure sensors are devices that measure pressure by relying on the deformation caused at a membrane. With the aid of different technologies, the deformation is converted into electrical signals for processing. There are several types of sensors based on the different measuring principles such as piezo-resistive pressure sensors with the Bosch BMP280 being a prime example, and capacitive pressure sensors such as the DPS368 [15].

1. BMP280

The BMP280 is a digital piezo-resistive pressure sensor. It measures pressure by relying on a micro-electro-mechanical system (MEMS) diaphragm allowing for a pressure measurement range of 300 hPa to 1100 hPa, with an absolute accuracy of ±1 hPa. Outputting pressure as a digital value, the BMP includes an internal ADC and low pass filtering units with a I²C digital interface where some compensation algorithms are required by the host MCU. Moreover, this model allows for a 0.16 Pa resolution [16].

2. DPS368

The DPS368 is a pressure sensor that bases readings off a capacitive sensing principle, offering a wide range of 300-1200 hPa alongside a ± 0.002 hPa sensor precision and an absolute accuracy equal to that of the BMP model. Its internal signal processor converts the output from the pressure sensor element to 24-bit results hence measurement is available through the serial I²C or SPI interface. Moreover, it includes a built-in ADC supports filtering as well as oversampling to deal with noise. Finally, it offers a 0.06 PaRMS pressure data resolution [17].

TABLE V. SUMMARY PRESSURE SENSORS' SPECIFICATIONS

Comparison	Pressure Sensors	
	BMP280	***DSP368***
Range	300-1100 hPa	300-1200 hPa
Absolute accuracy	±1 hPa	±1 hPa
Output interface	Digital (I²C / SPI)	Digital (I²C / SPI)

F. Accelerometers

Accelerometers are sensors that measure acceleration forces, which may be static, such as gravity, or dynamic, caused by movement or vibration. Types of accelerometers include piezoresistive, piezoelectric, servo, frequency-change, and capacitive. Despite differences in implementation, accelerometers generally operate by sensing the response of a mechanical sensing element, generating an electrical signal resembling an objects acceleration [18].

1. ADXL335

The ADXL335 is a 3-axis accelerometer, it relies on deflections of a moving mass caused by the acceleration, hence unbalancing a differential capacitor. This results in an acceleration proportional voltage output. Operating at a ±3.0 g range with an extended range of ±3.6 g without damage, this model includes an analog interface. This presents the need for an external ADC to digitize the analog signal outputted by the sensor. Moreover, bandwidth of the device is set by the user, this filtering improves measurement resolution. However, the accuracy factor is a combined effect of several error terms [19]:

- *Zero-g bias:* An error shifting entire measurement, ±0.15g.
- *Sensitivity Tolerance:* An error stretching or compressing the scale of measurement, ±1%.
- *Nonlinearity:* Error resulting from imperfect linearization, ±0.3% full scale.

2. LIS3DH

The LIS3DH is also a 3-axis accelerometer, it offers a 16-bit digital I²C/SPI serial interface standard output indicating the presence of an internal ADC. It also offers dynamically selectable ranges, ±2 g ±4 g ±8 g ±16 g with a sensitivity of 1, 2, 4, and 12 mg/LSB respectively as well as a ±40 mg zero-g bias while exhibiting a nonlinearity of ±0.5% of full scale [20].

LIS3DH has a competitive edge over the ADXL335 as it includes special features including a 10000g high shock survivability compared to the 3.6g of ADXL335. While both share the same operating temperature of -40°C to +85°C, LIS3DH also takes advantage of interrupt generation and a First-In-First-Out buffer all while operating at an ultra-low power mode down to 2 µA compared to the 350 µA typical power of ADXL335 [20].

TABLE VI. SUMMARY ACCELEROMETERS' SPECIFICATIONS

Comparison	Accelerometer	
	ADXL335	***LIS3DH***
Range	±3.0 g ,extended range : ±3.6 g	±2 g ±4 g ±8 g ±16 g
Zero-g bias	±0.15g	±0.04 g
Power	350 µA	2 µA
Operating temperature	-40°C to +85°C	-40°C to +85°C

III. ACTUATORS

A. Servo Motors

Servo motors are high specialized pieces of equipment designed for precise control of rotary or linear motion. It employs a feedback mechanism ensuring exact position. They are mainly characterised by the power source either AC or DC, examples on those would be the SGM7G and the SG90 respectively [21].

1. SGM7G

The SGM7G operates as a part of a close-loop AC servo system. It requires either 200 V AC or 400 V AC depending on the specific model to operate. In addition, due to the absolute encoder feedback, wiring is simplified and no homing routines are required. As a safety measure, servopacks are equipped with suppression features cancelling out the equipment's natural oscillation eliminating harmful artifacts. Furthermore, these motors offer up to 3,000 rpm speeds as well as a peak torque of up to 300 N.m [22].

2. SG90

The SG90 is a micro servo motor that can rotate up to 90 degrees in each direction. It operates at a DC voltage supply of 4.8 to 6.0 V and relies on pulse width modulation PWM signals to determine magnitude and direction of rotation. Moreover, it runs at a speed of 0.1s/60 degree with a 500-2400 µs acceptable pulse width as well as a stall toque of ~0.12–0.18 N·m making it suitable for lightweight applications [23].

TABLE VII. SUMMARY SERVO MOTORS' SPECIFICATIONS

Comparison	Servo Motors	
	SGM7G	***SG90***
Motion Type	Rotary continuous	Rotary limited
Range	Unlimited	±90°
Supply Type	AC	DC
Safety features	Vibration suppression	None specified

B. Solenoids

A solenoid is a device that relies on electromagnetism to convert electrical energy into mechanical motion. Fig. 1 below shows a solenoid's circuit diagram [24].

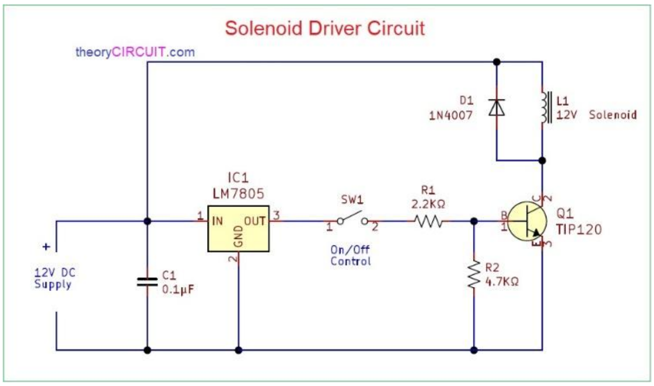

Fig. 1. Solenoid Driver Circuit

Moreover, solenoids are mainly characterized by their motion type, the section below discusses two solenoids differing in motion type [25].

1. RedHat II 8210G

The RedHat II is a linear motion solenoid used to actuate a valve, it has two discrete mechanical states depending on voltage supply. As voltage is supplied to the solenoid current flows and creates a magnetic field which consequently pulls a ferromagnetic plunger linearly opening or closing the valve. This solenoid operates at a voltage supply value of 24-480 V AC and 6-240 V DC depending on the specific model where no communication interface is needed, just a direct ON/OFF interface. It also includes a normally open/closed selection to avoid incorrect energization problems [26].

2. *CDR 030*

CDR 030 is a compact rotary solenoid suitable for positioning tasks where shot switching times and defined rotary movements are required. This model operates at a 24 V DC supply voltage with a 10-30 ms switching time with a rotational angle of 90 degrees. Moreover, controlling the rotation direction is controlled by the polarity of that DC supply [27].

TABLE VIII. SUMMARY SOLENOIDS' SPECIFICATIONS

Comparison	Solenoids	
	RedHat II	***CDR 030***
Motion type	Linear	Rotary
Rotation/stroke	Short linear stroke	90˚
Supply type	AC or DC	DC only

C. *Piezoelectric Actuators*

Actuators convert electrical energy into mechanical energy. Piezoelectric actuators rely on piezoelectric materials, capitalizing on their deformation when in the presence of an electric field. Unlike electromagnetic actuators that move loads using the interaction of magnetic fields at a distance, these actuators utilize the mechanical strain and internal stress in a material this is called the inverse piezoelectric effect [28].

For this piezoelectric effect to take place however, these actuators typically require a supply voltage of 50V to 200V [29]. Supplying this type of range differs as there are different types of electrical drive methods. They have a wide range of applications ranging from the medical industry to satellite technology, generally where precision and small space constraints are critical [28].

1. *LT20*

Classifies as a member of the LEGS Linear twin, the LT20 is a friction-based actuator, which uses contact friction between the drive leg and the drive rod linearly, all driven using a multi-phase waveform for full or partial steps (micro-steps). It also implies a power-off holding technique preserving power while in hold position. Furthermore, it operates at a range of 42-48 V, providing a 0-74.5mm range of motion and 0-24mm/s speed range with a nanometer-scale step resolution when micro-stepping [30].

This model tends to be used for advanced products such as optics, factory automation, and medical technology given its high precision and durability in design meaning reliable motion solution [31].

2. *LR17*

LR17 of the LEGS rotary family is a piezoelectric rotary actuator that is driven by a multi-phase piezoelectric excitation with an operating voltage in the range of 42-48 V. This model generates motion through a frictional drive principle. Equipped with a magnetic absolute encoder for position accuracy, this actuator is applied to optical alignment, rotary stages, and precision positioning.

Moreover, they provide high holding force without power with speed of range 0-44rpm. They also operate without magnetic fields and provide smooth motion. Although it shares many similar features to the LT20 they each have their specific application due to the different motion where LT20 are suitable for linear positioning and sliders, while LR17 is applied in optical alignment as well as precision rotary positioning [32].

TABLE IX. SUMMARY PIEZOELECTRIC ACTUATORS' SPECIFICATIONS

Comparison	Summarises Piezoelectric Actuator	
	LR17	***LT20***
Operating voltage	42-48 V	42-48 V
Motion	Rotary	Linear
Speed Range	0–44 rpm	0-24mm/s

IV. CASE STUDY: HVAC SYSTEM FOR CARS AND AUTOMOTIVE VEHICLES

The acronym HVAC stands for Heating, Ventilation, and Air conditioning. It is a network of subsystems working collectively to not only add heat or remove unwanted heat from the passenger cabin, it also purifies and circulates air throughout the vehicle, monitoring the cabin's overall environmental conditions.

In other words, it is an advanced system which enables independent regulation of cabin temperature and humidity. This can be achieved by monitoring and controlling the airflow and distribution inside the vehicle offering personalised comfort [33].

It employs multiple sensors transmitting continuous readings to the MCU as well as actuators responding to the MCU's directives taking the necessary procedures consequently providing the following key functions [34] as shown in Fig. 2 below:

- *Temperature Regulation:* Sensed by temperature sensors, MCU compares readings to preset values, drives heater/cooler.
- *Fogging prevention:* Sensed by both humidity and temperature sensors, MCU compares reading to threshold values, drives DC motor operating the blower fan.
- *Air Quality Control:* Sensed by gas sensors, MCU compares values to preset values, drives servo motors to open flaps.

Finally, the system can make use of piezoelectric actuators and pressure sensors by implementing warning buzzers signalling a significant rise or drop in refrigerant pressure, intermittent compressor faults, and expansion valve malfunction all flagged by a pressure sensor. This is the ultimate finishing touch to a system revolving around the comfort and safety of passengers in vehicles perfectly illustrating how sensors and actuators communicate to automate embedded systems all around us.

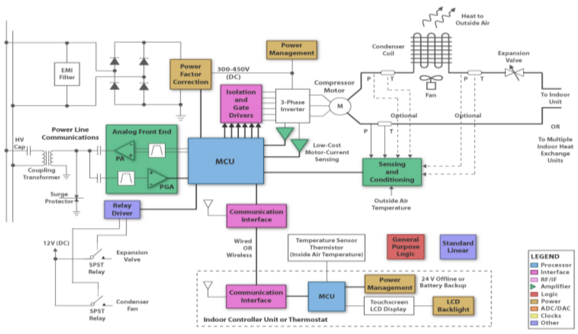

Fig. 2. HVAC diagram [35].

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