Programmable Logic Controllers (PLC’s)

Section A.1

Design Characteristics of Typical PLC systems

Definition of a PLC

“A programmable logic controller is a ‘digitally controlled operating system, designed for use in an industrial environment. It contains a programmable memory for storage of user-defined instructions for implementing scientific functions such as logic, sequencing, timing, counting and arithmetic, to control through digital or analogue inputs and outputs, various types of machines and processes”

(Programmable logic controllers and their engineering applications – Alan J Crispin ISBN 0-07-709317-8)

The definition above gives a good overview of a typical PLC system in terms of what it does. Fig.1 below shows a simplified block diagram of that system.

From the diagram we can see that the actual PLC has multiple inputs and outputs, and a method for communication between the user and the PLC. Connected to the inputs of the PLC would be various input devices which are contained within the machinery being controlled. Typical input devices used would be sensors capable of measuring changes in temperature, pressure, or motion etc. Connected to the outputs of the PLC would be output devices such as lamps, solenoid valves and contactors, capable of controlling operation of the machinery. The PLC itself needs a program (algorithm) to tell it what operation to carry out, in relation to changes in its inputs. This program is a series of instructions for the PLC written by the user, and downloaded to the PLC’s memory through a communication input i.e. RS232. The PLC will then, using its own internal program, scan the user program, read its inputs from the sensors and initiate appropriate outputs according to the user’s instructions based on the input states. The PLC will continue to scan its inputs and initiate its outputs according to the control program in a continuous control loop.
A more detailed block diagram of the PLC system can be seen in Fig.2 below. It shows the processor, power supply, input/output interface, program and data memory, and communications interface.

Fig.2 Detailed look at a typical PLC system (‘Programmable logic controllers’ W.Bolton)
Types of PLC System

Various types of PLC system exist, with the choice of system dependent upon the complexity of the control task, and cost. There are three typical system types, which are

**Unitary** - The unitary PLC system is a standalone unit, which is normally directly connected to the machine being controlled. It is commonly known to be the smallest and least expensive type of PLC, and would be used for small scale automation tasks where only a small number of inputs and outputs are needed, typically 8 - 100. They are normally programmed with handheld programming consoles which are connected directly to the PLC. The unitary PLC will consist of all of the features shown in the block diagram in Fig.2, all in one handy package. A typical example of a unitary PLC is the Mitsubishi FX2N-16M shown below in Fig.3.

![Mitsubishi FX2N-16M](image)

**Fig.3. Mitsubishi FX2N-16M**

<table>
<thead>
<tr>
<th>PLC Type</th>
<th>FX2N-16M</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Supply</strong></td>
<td>100-240V AC, 24V DC</td>
</tr>
<tr>
<td><strong>Inputs</strong></td>
<td>8</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
<td>8</td>
</tr>
<tr>
<td><strong>Digital outputs</strong></td>
<td>Relay, Transistor</td>
</tr>
<tr>
<td><strong>Program cycle period per logical instruction</strong></td>
<td>0.08µs</td>
</tr>
<tr>
<td><strong>User memory</strong></td>
<td>8000 steps PLC-Program (RAM internal), optional 16 k RAM/EEPROM</td>
</tr>
<tr>
<td><strong>Dimensions in mm (WxHxD)</strong></td>
<td>150x90x87</td>
</tr>
</tbody>
</table>
Modular – The modular system as the name suggests, is made up from separate hardware modules, which are interfaced together by means of a proprietary bus back plane, which they are plugged into. A typical modular system will contain a power supply unit, a CPU, and digital and analogue input and output modules. This type of system would be used, where a need for expansion of I/O’s or program memory might be needed, in terms of larger more complex control systems. Other examples of modules available in this type of system could be networking modules to allow programming from a remote location. A typical example of a modular PLC system is the MELSEC AnSH/QnAS range show below in Fig.4.

Fig.4. Mitsubishi MELSEC AnSH/QnAS modular PLC

<table>
<thead>
<tr>
<th>Type</th>
<th>MELSEC AnSH/QnAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Supply</td>
<td>100-240V AC/ 24V DC</td>
</tr>
<tr>
<td>Inputs/Outputs</td>
<td>32-1024</td>
</tr>
<tr>
<td>Digital Outputs</td>
<td>Relay, transistor, triac</td>
</tr>
<tr>
<td>Cycle period/log.instr.</td>
<td>0.25 - 0.33 μs</td>
</tr>
<tr>
<td>PLC program memory</td>
<td>8 to 60 k steps</td>
</tr>
</tbody>
</table>
**Computer Bus Based System (rack mounted)** – The bus based system, or as commonly termed rack system, consists of a computer controller (PC), which uses processor boards to control peripheral interface boards plugged into various racks on a common bus back plane. The user program, all modifications, and system monitoring, are all controlled from the user’s PC. Bus based systems are usually programmed using a high level language such as C or PASCAL, which is compiled and executed on the user’s computer, which in turn targets the hardware on the bus. Various international bus standards have been developed for this type of system (i.e. STE bus, VME bus, euro card), which allows for ease of use when designing a system using special purpose interface cards for a particular standardised bus. A typical example of a bus type system is the Allen Bradley PLC-5 system, which uses its own bus backplane called the 1771. A diagram of the system can be seen in Fig.5 below.

Fig.5 Allen Bradley PLC-5 bus system ([http://www.ab.com](http://www.ab.com))
Section A.2

Internal Architecture of a Typical PLC

The internal architecture of a PLC is basically the internal configuration of its hardware and software. The PLC is a microprocessor based system, and as such, consists of three very simple building blocks, the central processing unit (CPU), which controls and processes all operations within the PLC, the memory, and the input/output interface devices, each of which are semiconductor integrated circuits (IC’s). The CPU is provided with a clock signal, the frequency of which determines the operating speed of the PLC and synchronizes all the elements of the system. Each of the three system blocks are interfaced together by means of a bus. A bus is typically a group of lines (i.e. conducting copper tracks or ribbon cable) that allow electrical signals to be transferred in parallel between system components (digital signals within a PLC). There are three basic bus types, the data bus, address bus, and control bus. The PLC uses the data bus for sending data between the system elements, the address bus is used for sending locations for accessing stored data, and the control bus is used for communications between the I/O ports and the I/O unit. The typical internal architecture of a PLC can be seen in Fig.6 below. The I/O unit shown will consist of an ADC, DAC, and relay interface.

![Internal architecture of a PLC](image)

**Fig.6 Internal architecture of a PLC**

On the next page I will describe each of the components in more detail.
Central Processing Unit (CPU)

The CPU is a single microprocessor device used to control the operation of memory and I/O devices within the system and to process data in such a way as defined by the user program. Many different types exist from various manufacturers, but in essence they all contain the same internal structure. They consist internally of:

The arithmetic and logic unit (ALU)

Responsible for manipulation of data stored in registers, both arithmetically and logically i.e. addition, subtraction, AND, OR, NOT, EXOR.

The Memory (registers)

Known as registers within a microprocessor, and are used for temporary storage of data and addresses within the CPU, which are involved in program execution. In terms of storage space a register is either a byte (8 bits), a word (16 bits), or a long word (32 bits). Common register types are, the data register, the address register, the program counter, the flag register, and the stack register. The data register holds data that can be operated on by the ALU, an example being a bit pattern moved into a data register could be added or subtracted to a bit pattern in another data register. The address register is used by the programmer to specify source and destination addresses of data items that are to be manipulated. The program counter holds the address of the next instruction to be executed, which is incremented by the CPU. The flag register contains single bit indicators known as flags, the purpose of which is to hold information on the result of the most recent instruction that affects them. Common flags are a carry bit (represents either a carry or borrow in addition or subtraction operations), a zero bit (when an operation results in a 0 answer), a negative bit (indicates the binary sign of the result, either positive or negative), an overflow bit (set to one when operation results in an answer that is larger than the register size). The stack register is a register containing the address of the last item pushed on the stack. The stack is a region of memory used for temporary storage of instruction addresses and register values in a Last-In-First-Out (nested) structure. It is used for interrupts and subroutine calls.

The Control unit

The control unit is used to control timings of operations. The control unit consists of a set of logic gates and counters driven by a clock. The execution time of each of the instructions within the microprocessor takes a specific number of clock cycles. The clock cycle time is the reciprocal of the clock frequency, e.g. a 10MHz clock has a clock cycle of 0.1µs (1/10MHz).
Memory

Another group of semiconductor integrated circuits exist within the PLC, known as memory. The purpose of memory is for storage of groups of data (binary digits) at locations identified by unique addresses within the PLC. Memory IC’s have an address input which is commonly 16 bits wide, and an I/O data port (8 bits wide). The storage capacity of a memory device will be determined by the number of binary digits it can hold, e.g. a 1K byte device can store 1024 bytes of data. Within a PLC various memory types exist, each used for a different purpose. They are:

Read only memory (ROM) – This type of memory is used for storage of the PLC’s operating system and fixed data used by the CPU. As the name implies, this type of memory once written cannot be modified, hence, read only. This type of memory remains fixed, even when the power is switched off (non-volatile). There are other types of ROM that can also be included within PLC’s that do allow the user to erase and re-program, typically erasable programmable read only memory (EPROM), and electrically programmable read only memory (EEPROM). The purpose of this type of ROM is for storage of application software. EEPROM is programmed using a specialised programming device, and erased by exposure of its quartz window to ultraviolet light. EEPROM is programmed in the same way but is erased using electrical pulses.

Random Access Memory (RAM) – This is a volatile memory, meaning that once the power is removed, any data stored disappears. RAM can be both, written to, and read from. Within the PLC it is used for two purposes, storage of the user’s program, and for data storage relating to the status of I/O devices, and values of timers, counters, and other internal devices (data RAM). In the case of the user’s program, a battery is included so that the program does not disappear once the power is removed. The RAM used for data storage, commonly termed data or register table is split into various sections, with designated blocks of addresses set aside for the various information sets, i.e. a block for I/O addresses to store I/O device states, and a block for counter values, timer values etc. Various types of RAM used within different PLC’s, including, static RAM (SRAM), and dynamic RAM (DRAM). Typically DRAM is cheaper than SRAM but not as fast, with data access time of 50 – 60 ns, compared with 10 – 20 ns for SRAM.

Memory locations within a PLC are communicated by using a memory map. A memory map is a diagram that shows the user how address locations are allocated to RAM, ROM, and I/O devices. An example can be seen in Fig.7 on the next page.
Fig. 7 Typical PLC memory map
Communication Buses

Within the PLC, there are various lines of communication known as buses. A bus can be described by using the analogy of a public bus journey (Fig.8 below). Say that we have three separate Ulsterbuses, each of which is assigned a specific route with its own specific drop of points. Each of the buses will move people between destinations on its own specific route, dropping them off and picking others up between stop off points. In terms of a PLC, the three Ulsterbuses would represent the three common bus types, the data bus, the address bus, and the control bus. The people on board would represent the digital information that is transported between locations (in parallel), which can be one way or bi-directional dependant on bus type. The routes (road) belonging to each bus represent the set of lines (copper tracks, or ribbon cable) that link the various components on each bus. The drops off points (bus stops) represent the various locations that digital data is either sent to or retrieved from i.e. microprocessor, memory and I/O addresses.

Fig.8 PLC bus analogy

On the next page I will talk about each of the three bus types in detail
**Data bus** – The data bus allows bi-directional (two way) data flow between the microprocessor, memory, and I/O’s. The capacity for data to flow is determined by the microprocessor. An 8 bit microprocessor has a data bus that is 8 lines wide, and likewise a 16 bit processor, 16 lines wide. Simply put, the data bus carries the actual data being processed within the PLC.

**Address bus** – The address bus allows uni-directional (one-way) data flow through a set of lines carrying binary number addresses. The CPU generates the addresses during execution of a program to specify source and destination points of various data items being moved along the data bus. The purpose of an address is to identify a particular memory or I/O location. To put it simply, the address bus carries information on which device the CPU is communicating with.

**Control bus** – The control bus is a set of signals generated by the CPU with the purpose of controlling system devices. The control bus carries commands from the CPU to the system devices, and returns data on the status of the devices. An example is a read-write control line which will select either a read or write operation depending on whether the CPU is inputting or outputting data to or from the data bus.

All digital devices sharing a common bus must be what are termed, tri-state. What this means is basically that as well as the condition logic 1 (on), and logic 0 (off), a third state of high impedance must be available. This high impedance state effectively removes the output from the circuit. In effect, the control bus uses this as a way of connecting various devices to the data bus.

**Input / Output Interfaces**

To enable connection to, and output from a PLC requires various interfaces. Within a PLC these interfaces come in the form of special purpose peripheral I/O semiconductor integrated circuits. These devices enable the microprocessor to interface with various external devices, e.g. programmable series/parallel interface devices, keyboard controllers, and counter or timer devices. Other front end circuits are included that enable interfacing between the PLC and external devices such as sensors, and actuators. These include on the input points, D.C. and A.C. voltage digital input circuits, pulse counter circuits, and analogue to digital (ADC) interface circuits. On the output points, included are, relay output circuits, transistor output circuits, triac circuits, and digital to analogue circuits.
Section A.3

CPU Operation Characteristics (Program Execution)

From Fig.9 below, I shall attempt to explain the operations of the CPU within the microprocessor, in terms of execution of the user program.

A PLC will run a user’s program in a loop as shown in Fig.9 (Run mode), where by checks are made on the inputs at periodic intervals and the program is run through in steps, and then repeated. This type of program execution is known as cyclic scanning.

The execution of the user program is illustrated on the following page with reference to Fig.9 above.
Program execution occurs in the following order:

1. The system inputs are scanned, with an image of their states then stored in fixed memory locations.
2. The user inputted ladder logic program is then executed rung per rung.
3. System output states are determined. This is achieved by scanning the program and solving of logic at the various rungs. An image of the output states are then stored in a fixed memory location.
4. The value of the output states held in memory are used to set and reset the physical outputs of the PLC at the end of the ladder program scan through the appropriate output hardware interfaces.
5. The process is then repeated over and over in a continuous loop.

The amount of time it takes for the PLC to run one cycle, i.e. scanning inputs, executing ladder program, and updating physical outputs is known as the scan time (Fig.10).

Fig.10 Representation of scan time
The scan time varies between PLC’s. An example of a typical scan times for a Mitsubishi FX1S PLC, along with calculation of scan time, can be seen in fig 11.

Scan time = Average execution speed per program step x Maximum program memory

For FX1S average execution speed per step = (0.55μs + 0.7μs) / 2 = 0.625μs/step

Maximum program memory = 2k steps = 2000 steps

Scan time = 0.625μs x 2000 = 1.25 ms

Fig.11 Example of typical scan time for Mitsubishi FX1S PLC (spec taken from, http://www.ab.com/programmablecontrol/plc/micrologix1000/)

What if a fault occurs in the equipment being controlled?

In Fig.9 another mode of operation is shown, called halt mode. If a fault is flagged when the PLC scans its inputs, then instead of running through the user’s program, a signal will be sent to the CPU to tell it to stop execution of the program, and instead run another program stored in another part of the memory until such time as it can resume. This so called halt mode of operation is commonly termed an interrupt, and is basically an interruption in the sequential execution of a ladder program.
A more detailed flow diagram of PLC operation and program execution, with detailed interrupt operation, from power up and initialization can be seen Fig.11 in below.

Fig.11 PLC operation and program execution loop diagram

http://www.mikroe.com/en/books/plcbook/app_c/app_c.htm
Section A.4

A typical PLC contains various Input and Output IC’s, which allow external devices to be interfaced with the PLC. Descriptions of these interface circuits, input and output, as well as external sensor devices follow.

(I) PLC input interface’s

**Analogue to digital converter interface (ADC)**

The diagram below shows a typical analogue to digital converter IC, as commonly used within the PLC.

![Fig.12 Analogue to Digital Converter IC (8 bit ADC)](image)

An ADC accepts an analogue input signal, either voltage or current, and converts this to an output binary value (digital) corresponding to the magnitude of the analogue input.

The ADC shown in fig.12 is an 8 bit model, consisting of output data lines D0 to D7, and inputs IN0 to IN7. Two other pins included are the start convert (SC) pin, and end of convert pin (EOC), which together with the ADC’s internal circuitry form a sample and hold circuit. In our diagram the ADC is shown in a standalone format, but conventionally within the PLC its operation is controlled by the PLC’s microcontroller. The SC signal is pulsed by the microcontroller, the ADC will then sample and hold the analogue input value, before converting it to a digital binary value (shown in this case by LED’s), when the conversion is completed, an EOC signal is sent to the microcontroller. The time taken for this conversion from analogue to digital is known as the conversion time. The conversion time varies between ADC’s, dependent upon the principles upon which they work. Typical methods of operation are successive approximation or flash conversion, with the later being the fastest. Flash converters simultaneously determine all the bits for the digital number representing the analogue input.
Successive Approximation

The successive approximation method obtains a short conversion time in the following way. The output of a DAC is compared with the analogue voltage or current to be converted by making a series of successive approximations of the value of the binary number required. This is done by using a special counter known as a successive approximation register (SAR). Fig.13 below shows a typical example of how the circuitry looks.

![SAR circuitry](image)

Anti-Aliasing

An error known as aliasing occurs in an ADC when the input signal is sampled too slowly. Sampling of the input signal should in theory be twice as fast as the inputs highest frequency component. When this is not the case the high frequency input value is represented by an erroneous lower frequency value. To prevent aliasing a common technique used is the addition of an anti-aliasing filter preceding the ADC. This filter bandlimits the input signal to half the sample frequency, thus sampling always occurs quicker, therefore no aliasing.

Quantization

Another factor when considering an ADC is quantization of digital binary values with regard to analogue signal input values. An explanation of what this means can be shown by using the example of the 8 bit ADC in fig.12. For an 8 bit ADC we have 256 bytes (2^8), these 256 discrete levels are known as quantization levels. If we take the range zero to 256, then there are 255 steps. If the ADC is designed for 5V operation, then the ratio of the maximum voltage of the input signal, over the number of
quantization levels, will give the resolution, or as commonly termed quantization interval. In our example the ADC is designed for 5V operation, and we have 255 quantization levels, therefore 5/255 equals 19.6mV. This means that every 19.6mV on the input represents a different binary number on the output; hence this is how the input voltage (or current) is quantified in terms of which digital binary number it represents. The only way to increase the resolution, or in other word make the system more precise, is to increase the number of bits used in the conversion. For example, by using a 12 bit ADC, the number of quantization levels are increased to 4096 (2^12), therefore resolution will be 5v/4095 steps, which equals 1.22mV.

**ADC Inputs**

The input range of the analogue input to an ADC can either be uni-polar (e.g. 0-10v), or bi-polar (e.g. -10 to +10v). They can also be set up in a variety of different ways, i.e. single ended input, or differentially. With the single ended input, one of the terminals will be connected to ground (0v); therefore the signal will vary with respect to 0v. Differential inputs are used to measure the difference between two signals, which can be a useful method when noise is a problem, as the noise on both signals is effectively cancelled out, this is where the term noise immunity comes from. In industry it is common place to use, currents rather than voltages for PLC ADC inputs, simply due to voltage drops incurred because of cable lengths. Voltage measured at the input to a cable will be more than voltage at the other end of the cable; whereas current will be the same, no matter what length the cable is. The typical current range used in industrial applications is 4-20mA, this allows a broken cable to be pinpointed easily, as current will equal zero if a fault has occurred (this is used within the system to indicate a fault). The current input to an ADC is measured by measuring the voltage across a known resistance, and applying ohms law (I = V/R).

**D.C. Voltage digital input circuits**

Within the PLC, 24V D.C. circuits are employed for the connection of current sinking, or current sourcing input devices. Fig.14 below shows schematics for both types of input circuitry.

![Fig.14 PLC current sinking and sourcing circuitry](image-url)
Operation

For a PLC’s input circuit to operate current must flow by entering at one terminal and exiting at another. This means at least two terminals will be associated with each I/O point. The main current path will be the input terminal to output terminal. Another terminal will provide a return path to the power supply. Combined together both these routes provide a loop that allows current to flow.

In terms of the current sinking input interface above, when the input device is turned on it will connect the circuit to the 0v line of the 24v D.C. supply. Current will then flow through the status LED which will emit light, causing the photoelectric transistor to conduct. The purpose of the photoelectric transistor is to provide a degree of isolation between the input device and the CPU. This is achieved by providing separate supplies for the LED and the photoelectric transistor circuit.

In terms of the current sourcing input interface, when the input device is turned on a connection is made to the positive polarity of the 24v supply which causes current to flow from the supply through the status LED, thus causing the photoelectric transistor to conduct.
(II) PLC output interfaces

**Relay Output Circuit**

A PLC output interface circuit commonly used to control output devices is the relay output circuit (Fig.15). The relay output is normally used when switching large power loads such as motors.

The PLC's CPU outputs a signal to activate the NPN transistor, which switches current through the relay coil to close its contact. The diode shown across the relay prevents back e.m.f, thus providing protection to the transistor. Back e.m.f is caused when a reverse voltage induced in the relay's coil causes an inductive current to be sent backwards into the system against the conventional flow of current. This problem occurs when inductive loads are connected, in this case the relay coil. Both A.C. and D.C. loads can be supplied by connection to the relay output terminals. Relay outputs are normally specified in terms of their rated voltage and rated current. The rated voltage is basically the suggested voltage needed for operation of the coil. If the voltages used are too low, this results in non operation, and if voltages used are too high, this will dramatically shorten the relay's life. The rated current is the maximum current that the coil can support before contact damage would occur, such as melting or welding. Typical relay specifications for a Toshiba T1 PLC in terms of rated current and voltage can be seen in Fig.16.

![Fig.15 Relay Output Circuit](image)

![Fig.16 Typical relay output spec for Toshiba T1 PLC](image)

<table>
<thead>
<tr>
<th>Relay Output Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output points</td>
</tr>
<tr>
<td>Maximum voltage</td>
</tr>
<tr>
<td>Maximum Current</td>
</tr>
<tr>
<td>Minimum load</td>
</tr>
<tr>
<td>ON/OFF delay time</td>
</tr>
</tbody>
</table>
**Transistor Output Circuit**

A typical opto-isolated transistor output is shown in Fig.17.

![Transistor Output Circuit Diagram](image)

Fig.17 PLC transistor output circuit

The transistor output circuit is used by the PLC to switch D.C. voltages. For operation the transistor switch relies on there being an open circuit between the collector and emitter when the base-emitter circuit is not forward biased, and there being a short circuit between the collector and emitter when the base-emitter circuit is forward biased. The switching action ideally requires that the base current is large enough to allow the collector current to reach its maximum saturation value; at this point the voltage drop between the collector and emitter is extremely small. What this means is that, the collector is close to 0v and the collector current may then be roughly determined from the load resistance and supply voltage. Typical transistors used are either NPN or PNP, and depending on the manufacturer the type of transistor can either be bipolar junction transistors (BJT), or Metal Oxide Semiconductor- Field Effect Transistor (MOS-FET). The operation of the circuit shown in fig.17 begins when the CPU sends a signal to the opto-coupler by supplying a small voltage to the LED; the LED then emits light which is seen by the receive side of the opto-coupler, which then allows a current to flow. This current then turns on the base of the transistor connected to the output. Any load connected between the output and ground will then be switched on.
(II) PLC sensing devices

**Thermocouple**

A type of sensing device that measures temperature is known as a thermocouple. A thermocouple converts temperature into a voltage. Therefore a change in temperature will equal a change in voltage.

The physical make up of a thermocouple is quite simple. It consists of two wires made from different metals connected at a junction. The voltage is produced by an effect known as the thermoelectric effect. The thermoelectric effect was first noticed by Thomas Johann Seebeck in 1821. He found that a conductor will generate a voltage when subjected to a temperature gradient, and to measure this voltage a second conductor is used that generates a different voltage under the same temperature gradient. The voltage difference between the measured voltages is then calculated, and this value is then related to the temperature gradient. To enable us to read absolute readings the temperature difference is referenced to a known reference temperature. An illustration can be seen in fig.18, with a physical representation in fig.19.

![Typical thermocouple circuit illustration](image18)

*Fig.18 Typical thermocouple circuit illustration*

![Physical representation of a thermocouple](image19)

*Fig.19 Physical representation of a thermocouple*
The relationship between temperature and voltage for a thermocouple will be non-linear, meaning that the output voltage will not be proportional to temperature. There are various types of thermocouple available and they are given designator letters which correspond to their specification, as shown in fig.20 below.

![Fig.20 Types of thermocouple and their specification (Wikipedia)](image)

The output voltage of a thermocouple will typically be in the microvolts and therefore need to be amplified before being interfaced with the PLC by way of an ADC circuit. This is normally achieved by the use of an amplifier circuit incorporating an operational amplifier, a typical example is shown in fig.21.

![Fig.21 Typical thermocouple amplifier circuit](image)
**Strain Gauge**

A strain gauge is a transducer consisting of an electrically conductive material which has a special strain/resistance relationship. The strain gauge is bonded onto the surface of a mechanical system component (e.g. a beam or bar) in which strain is to be measured (fig.22).

![Fig.22 Strain gauge application](image)

The strain/resistance relationship originally reported by Kelvin in 1856 is the ratio of the relative electrical resistance change of the conductor to the relative change in its length. This is called strain sensitivity (gauge factor) and is a function of the dimensional changes that take place when the conductor is elastically deformed with any change in the resistivity of the material with strain.

The formula giving the electrical resistance of a conductor is:

\[ R = \frac{\rho l}{A} \]

Where:
- \( R \) = resistance
- \( \rho \) = resistivity
- \( l \) = length
- \( A \) = cross sectional area

The formula for strain sensitivity (gauge factor) is given by:

\[ G = \frac{\frac{\Delta R}{R}}{\frac{\Delta l}{l}} \]

Where:
- \( G \) = gauge factor
- \( R \) = initial resistance
- \( \Delta R \) = change in resistance
- \( l \) = initial length
- \( \Delta l \) = change in length
The gauge factor of various types of material can be seen in fig.23.

<table>
<thead>
<tr>
<th>Type and Class</th>
<th>Gauge Factor $F$</th>
<th>Temperature Coefficient $F$ (ppm/K)</th>
<th>Thermal Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous, metals</td>
<td>2</td>
<td>400</td>
<td>Fair</td>
</tr>
<tr>
<td>Discontinuous, metals</td>
<td>Up to 100</td>
<td>$\sim$1000</td>
<td>Poor</td>
</tr>
<tr>
<td>Continuous, metal alloys</td>
<td>2</td>
<td>$\sim$100</td>
<td>Good</td>
</tr>
<tr>
<td>Discontinuous, metal alloys</td>
<td>Up to 100</td>
<td>$\sim$1000</td>
<td>Poor</td>
</tr>
<tr>
<td>Ceramics</td>
<td>Up to 100</td>
<td>200–1000</td>
<td>Generally Good</td>
</tr>
<tr>
<td>Semiconductors</td>
<td>Up to 100</td>
<td>$\sim$1500</td>
<td>Good in some cases</td>
</tr>
</tbody>
</table>

Fig.23 Typical gauge factor of various materials used in strain sensors ("Survey of instrumentation and measurement" Stephen A. Dyer)

Various types of strain gauge exist including un-bonded wire, bonded wire, bonded foil, semiconductor, and thin film.

**Un-bonded wire**
This consists of a strain sensitive wire mounted on a mechanical frame whose parts can have slight movement in respect to each other. This movement causes a change of tension in the wire which results in a change in electrical resistance. The relative resistance change measured is a measure of the relative strain.

**Bonded wire/foil**
This consists of a strain sensitive wire or foil entirely attached with an epoxy resin adhesive to the component being measured for strain.

**Semiconductor**
This type of gauge developed using semiconductor doped silicon materials offers an ultra sensitive means of measurement for use where extremely small strain needs to be measured. Gauge factors of 10 – 130 are typical. An example of a silicon strain gauge can be seen in fig.24

Fig.24 Silicon semiconductor strain gauge
Thin film
Strain gauges manufactured from thin film technology are made using any desirable resistor metal, metal alloy, semiconductor, or a combination of metal and dielectric known as cermets. An example is shown in fig.25.

Fig.25 Thin film strain gauge
**Strain gauge operation**

The strain gauge is connected to a circuit known as a Wheatstone bridge. The Wheatstone bridge is a measurement instrument designed by Samuel Hunter Christie in 1833, and later improved by Sir Charles Wheatstone in 1843. The Wheatstone bridge can be seen in fig.26 with the strain gauge configuration.

![Wheatstone Bridge Circuit](image)

**Fig.26 Wheatstone bridge Circuit**

The Wheatstone bridge allows precise measurement of the very small resistance change in the strain gauge brought about when strain is applied. For bridge balance the condition is $R_1/R_2 = R_3/R_4$. Whilst in a balanced state, any change in the strain gauge resistance will cause unbalancing of the bridge and a voltage will then be detected. To compensate for changes in resistance of the gauge due to temperature change a dummy gauge may be connected. An instrumentation amplifier is then used to feed the balance signal to an analogue to digital converter for reading by the PLC's CPU. The general output equation used for a Wheatstone bridge is shown below:

$$V_{out} = \frac{F\epsilon V_{in}}{4}$$

Where:
- $F$ = Gauge factor
- $V_{in}$ = bridge input voltage
- $\epsilon$ = Strain
- $N$ = number of active arms of the bridge

To put it more simply the operation of a Wheatstone bridge/strain gauge can be put into a few easy steps:

1. The strain gauge is connected to the Wheatstone bridge
2. The bridge is excited by an external stabilised D.C. supply
3. A stress is applied to the strain gauge where a change in resistance takes place unbalancing the bridge
4. A voltage signal is outputted typically millivolts relating to the stress value
5. Instrumentation amplifier is used to amplify the signal to a level suitable for the ADC
6. The binary data from the ADC is then read by the PLC's CPU
Section A.5

PLC Communication Links

PLC’s transfer digital information between various pieces of equipment (e.g. to programming modules and PC’s) by means of communication links, in either point to point link, or through a network. Digital data can be transferred in two ways, either serially or in parallel.

Serial communication involves the transfer of data one bit at a time in what is termed a bit stream; whilst Parallel data on the other hand sends a complete data word (commonly 8 bits) at once.

Various mediums are used to allow this data to travel between devices. The common cable types are screened twisted pair (CAT 5), co-axial, and fibre optics.

Screened Twisted Pair

Information transferred serially normally uses two wires, one for transmitting, and one for receiving. Twisted pair as the name suggests, consists of two insulated copper wires. To reduce the chances of picking up any stray external electromagnetic waves, and thus distorting the data being transferred within the cables they are twisted together. Another measure taken to reduce the chance of cross coupling is that they can be wrapped in a either a metal foil or braid, which is grounded. The whole cable is then wrapped in an external insulating material. This type of cable normally consists of multiple twisted pairs (i.e. CAT 5 or CAT 5e cable), with each pair being a combination of solid colour and striped, with a different colour used for each pair. The number of twisted pairs used are dependant upon the use, eg analogue, digital, or ethernet. An example of CAT5 cable with specifications can be seen in fig.27 below.

![Fig.27 CAT5 twisted pair networking cable](image)
Co-axial cables

Used for connection of PLC’s and PC’s to ethernet systems and various types of local area networks where communication over a large distance is needed. Typical types for PLC networking include RG58 and RG59. Co-axial consists of an inner rigid copper conductor surrounded by a tubular insulating layer of PTFE, which is flexible and has a high dielectric constant. This is then surrounded by a concentric finely braided grounded shield, and then by an insulating plastic jacket. Co-axial cable has a characteristic impedance depending on its dimensions, and the dielectric constant of the insulator. The impedance is the ratio of the voltage to the current in the cable \( R = V/I \) and will either be 50 ohms or 75 ohms. This impedance must be matched to the circuit it is connected to, thus preventing the signal from being degraded by standing wave reflections. Fig.28 below shows the construction of coaxial RG59 with the common BNC connectors used cable.

![Coaxial cable and BNC connectors](image)

**Fig.28** RG58/59 Coaxial specification, connectors, and cable construction
Fibre optic cable

This type of cable has replaced a lot of coaxial copper cable for networking of PLC’s especially in large networks requiring connection between servers, PC’s and PLC,s. It consists of a core containing a number of thin silica glass or plastic strands surrounded by a cladding of the same material but with a lower refractive index, this is then surrounded in an external coating known as a buffer. A laser is directed into one end of the cable which creates an electromagnetic carrier wave, that is then modulated to carry information at extremely high speeds. Advantages of fibre optic over traditional copper cables are, higher bandwidths (more information can be carried), no cross talk, and the cable can be installed in areas where there is a large amount of electromagnetic interference meaning greater efficiency as less information needs to be re transmitted, and less attenuation. Fig.29 below shows the construction of fibreoptic cable.

Fig.29 Cross section of optical fibre cable.
(http://www.ncdot.org/doh/PRECONSTRUCT/traffic/itss/ws/manual/tms2.pdf)
6. State the general input and output specification for the FX0N series, in terms of voltage and current limits, and also how the external devices are coupled to the PLC.

The general input and output specifications for the Mitsubishi FX0n range are:

**Input:**
- d.c. input 24V 7mA opto-isolated

**Output:**
- Relay 250Vac, 30V dc 2A per point
- Transistor 30Vdc, 0.5A prepoint 0.8A max per 4-point gang

The external devices are coupled to the PLC by means of an opto isolator.

7. What is the analogue voltage and current range for such a PLC if the FX0N_3A A/D – D/A converter module is used?

**Voltage range:** 0 – 10 V

**Current range:** 4 – 20 mA

8. State the function of the F2-40BL lithium battery, as used with the FX range of PLC’s. Would a PLC using an FX-Eeprom-8 as its sole data storage facility require such a battery? Explain.

RAM programme memory is volatile meaning it will lose its stored information when the power is removed. The purpose of the battery is to keep the RAM programme memory active after power down. If an 8K Ram memory cassette was to be used in the FX range, battery life would last for approx 3 years. If an FX Eeprom-8 is fitted to a PLC as its sole data storage it will not require a battery due to the fact the chip used does not require power to retain its memory. The power is only required if the memory needed to be rewritten.

9. Briefly describe the main difference between the new enhanced version of 3.07 CPU, as used with the FX range of PLC’s and its predecessor.

The new enhanced version CPU 3.07 has an enhanced programming set with additional functions such as SQR, SORT, SER and PID, enhanced communications capability with the addition of RS232 and RS485 software control, and an additional 2000 RAM file registers. Programs written for older models will work without any modifications needed to the hardware, and older programs should run with only a few exceptions. Processor speed has also been improved, an example is that the basic instruction set now executes at 0.48µs compared to its original 0.78µs.
10. The FX family of PLC’s is designed to include a flexible range of communication options. State the main difference between the FX2-40AP and the FX-323AW interface adapters.

The FX2-40AP is a parallel link adaptor used in applications where two machines are to have their operation synchronized. The FX232-AW is a serial interface that allows computers or intelligent machine interfaces to be connected to the programming port of all FX controllers. Both units provide full isolation by means of opto isolators on the communication lines protecting against over voltage. The main difference in terms of feature is that the FX-232AW is able to manipulate modems as it has an automatic carrier detect facility, meaning that when it is dialling out through a modem it can detect when the telephone line connection is made. This makes modem communications quick, easy and more efficient.

11. Describe how two machines can have their operation synchronised or co-ordinated using PLC’s and FX2-40AP units

When using the FX range two machines can have their operation synchronised by means of an FX2-40AP (parallel link adaptor). This unit will link two PLC’S together, one as master, and the other as slave. Communication between the two is normally by fibre optic or twisted pair cables. The main advantage being that both main processor units (MPU) are still intelligent, e.g. they can use each others programs and carry out completely differing tasks.

12. Document three examples of industrial control applications that make use of different design characteristics of PLC’s.

In industry PLC’s are used to control various processes, this could be in manufacturing, power generation, water treatment, the list is endless.

The case studies on the following pages are taken from [www.automation.com](http://www.automation.com) document three realworld industrial applications where PLC systems have been utilised to solve a problem.
Case study 1: Intelligent valve actuation at Severn Trent Water’s “beacon project”

Rotork has supplied over 250 Profibus network-enabled IQPro intelligent electric actuators for valve control throughout the new and refurbished plant areas. The actuators are linked on fully redundant Profibus field networks to Allen Bradley PLC platforms at intelligent motor control centres (iMCCs) throughout the site.

Severn Trent Water’s Minworth sewage treatment works, which serves around 1.75 million of Birmingham’s population, is undergoing a major modernisation project that will improve the quality of the water put back into the River Tame and significantly upgrade the work’s facilities, improving the quality of the 1.6billion (one billion litre) daily treatment capacity. The £145 million project is being handled by an alliance comprising Severn Trent Water, North Midland Construction Nomenca and Binaner, with Pick Everard as consultants. It will create one of the world’s most efficient and technologically advanced large scale treatment works.

Tony Wray, chief executive officer of Severn Trent Water, has praised the scheme as a “beacon project”, adding that the 30-strong supply chain should be proud of the numerous achievements at Minworth. As a member of this supply chain, Rotork has supplied over 250 Profibus network-enabled IQPro intelligent electric actuators for valve control throughout the new and refurbished plant areas.

Many of the actuators are installed on the new eight-lane inlet works, the new 22 primary settlement tank island and the enlarged activated sludge plant. In all areas Rotork IQPro multi-turn actuators operate penstocks to control the flow through the works; whilst on the activated sludge plant, IQPro direct drive quarter-turn actuators are also installed on the air flow control valves that regulate the introduction of air into the treatment tanks.

The actuators are linked on fully redundant Profibus field networks to Allen Bradley PLC platforms at intelligent motor control centres (iMCC’s) throughout the site. These interface with the site’s Rockwell SCADA system, which is accessible at local HMI terminals at key site locations. Feedback from sensors throughout the plant is used to automatically operate the actuators to account for fluctuations in flow, caused, for example, by storm conditions, and to enhance the efficiency of operations. The software for the SCADA system has been written by Softwire Controls and the whole network has been designed to provide extended information and historical trending for energy management and condition monitoring.

Assisting this function, data loggers in the Rotork actuators store a commissioning ‘footprint’ of valve operating torque and a torque curve for all subsequent valve operations. This data can be downloaded and analysed with Rotork IQInsight software in order to identify and plan valve maintenance requirements. The technology assists the optimisation of plant utilisation and eliminates the need for over-cautious maintenance scheduling.

As a further assistance to maintenance, all the actuators utilise Rotork’s ‘bumbleless’ Profibus interface module, which enables individual motorised valves to be disconnected without disrupting communication with the other devices on the network.

The new Rotork actuators join hundreds that are already installed at Minworth. Most have been fitted during previous modernisation programmes at the site and supplied through the long-standing framework agreement that Severn Trent Water has with Rotork.
Case study 2: Better hardware better bottle

Amcor, Australian owned packaging company, recently completed a two-year overhaul of a manufacturing information system at its Gresford, Wrexham, PET bottle manufacturing plant.

When you manufacture over ten million containers a day it is important to ensure reliable and accurate production. That is just what Amcor engineers, with the help of machine vendors, SolutionsPT, claim to have achieved at the Gresford plant.

Once it was decided that a plant-wide SCADA should be installed Amcor turned to SolutionsPT for Wonderware InTouch SCADA and real-time database InSQL.

The acquisition of data from the plastics machinery required test data access without affecting controller cycle time. A pilot design was developed and tested prior to deployment across 28 machines.

Using an Advantech Touch Screen PC, the basic scheme acquires data from a tag server. In turn, it also supplies the tag server with data from the machine’s logic controller. In order to do this unobtrusively, and to allow the Touch Screen PCs to have a good response, Amcor employed the use of a Woodhead Applicom PCU2000ETH Intelligent communications card. This was mounted in the PC and connected by Ethernet to the PLCs. The card handles all communication ‘on-board’ and thereby relieved the PC from this task. Data rates are over 100 words in <100 ms periods, plus an additional 3000 words every eight seconds.

In a bid to provide extra protection to the shopfloor PCs, Amcor mounted the units in the H section steelwork that supports the roof.

Further to the data available in the logic controllers, various data was required from non-intelligent electrical devices. SolutionsPT supplied an Advantech ADAM 3000 Modular I/O system; allowing particular points in the electrical scheme (both digital and analogue) to be sampled and connected back to the tag server via Ethernet. An output is also used to switch a machine-mounted beacon on to warn of threshold alarm levels being reached.

The Amcor plant is big and involves large distances for factory networking. Hirschman equipment provides network ring monitoring and 64 RJ45 points of connection for equipment and servers.

The associated server equipment is situated in the company’s main site server room, alongside Amcor’s business servers. A new rack was needed to run the various Wonderware components. A 19” rack system with 5 Advantech servers, shared screen and keyboard administration system, network hubs and UPS was designed, configured, tested and documented by Solutions PT’s hardware group.

Some of the servers (notably the Tag Servers) operate in master/slave mode, the InSQL server chassis has a dual power supply system and all the servers have RAID drives. Protection against mains noise, brownouts and blackouts is provided by a rack-mounted on-line UPS.

Amcor engineers were ‘skeptical’ about using touch screen PCs on the shopfloor, said Stuart Griffiths, process improvement team leader at Amcor.

‘However, our experience is that they are extremely durable and very simple to clean,’ he added.

Griffiths took the new solution to the machine operators and trained them in the use of the system.

Fine resolution data, a hallmark of real-time information, is said to be providing machine process insight that was previously unavailable to the Amcor engineers.
Case study 3: Buhler’s Grain Milling Automation Relies on OPC Technology

Buhler standardized on Softing’s S7/55 OPC Server to provide reliable connectivity between its WinCoS.r2 grain milling automation system and multiple S7-400 PLCs.

Buhler, the leading provider of grain milling solutions, standardized on Softing’s industry-hardened S7/55 OPC Server to provide reliable connectivity between Buhler’s “WinCoS.r2” automation system and multiple S7-400 PLC’s

Buhler is a global specialist in the field of plant design and construction and the related services for transforming renewable and synthetic raw materials into high-quality functional products and valuable substances. Buhler employs some 6,900 employees around the world and is headquartered in Switzerland. Most people are not even aware of how many times a day they encounter products to which Buhler has contributed. Breakfast rolls in the morning? The ink on the newspaper? Perhaps a few noodles for lunch? That refreshing beer after work? Yes, a bit of Buhler is in all of these things - for Buhler is a technology group and global market leader in Food Processing, Chemical Process Engineering, and Die Casting.

Approximately eight (8) years ago, Buhler’s grain milling business unit introduced WinCoS, a very successful automation system to control the grain milling process. WinCoS is a perfectly matched software and hardware solution for controlling processes. The process control system builds upon an automation concept that is tailored exactly to the specific requirements of a specific production plant - from simple starter versions to the maximum level of automation.

WinCoS enables a customer to cut its operating expenses (manpower, energy, maintenance, etc.), to increase the efficiency of the production process on the basis of characteristic figures, or to improve the quality assurance (HACCP, ISO, product re-tracing, etc.).

The latest version of Buhler’s automation system, WinCoS.r2, is based on standard components from Microsoft (operating system), Siemens (automation technology), and Softing (OPC communication). Starting with WinCoS.r2, Buhler’s design team decided to standardize on OPC as the main communication protocol to the process peripherals. “OPC technology enables us to seamlessly integrate best-in-class automation equipment from various vendors” said Kurt Geiger, Manager of Buhler’s Automation Standards Team. “We standardized on Softing’s S7/55 OPC Server to achieve OPC connectivity to our S7-400 PLCs. After evaluating numerous OPC solutions offered in the market, our communication experts chose Softing’s product because of its superior performance, outstanding reliability, and ease-of-use.”

Buhler’s grain milling automation systems are designed to run around-the-clock 24/7. Large installations utilize multiple high-end S7-400 PLC’s that provide up to 60,000 data points that the OPC Server has to process simultaneously. Failure is not an option given the fact that Buhler’s mills are handling 300,000,000 tons of wheat world-wide.

“Our decision to go with Softing turned out to be an excellent pick for Buhler,” said Kurt Geiger of Buhler. “Softing’s flexibility in supporting our ever changing requirements helps us to continually improve our system and to stay ahead of our competition.” For example, Softing enhanced its S7/55 OPC Server with functionality that enables Buhler to download new program versions to a S7-400 PLC on-the-fly without shutting down the milling process.

Continued over the page
Ease-of-use and Line Redundancy Support
Softing’s S7/S5 OPC Server offers the capability to import the symbolic names table of the Step7 program, eliminating the need to manually define all name tags in the OPC Server. Access to the S7 controller is accomplished via Ethernet, PROFIBUS, USB, or a serial communication link. The integrated server-side OPC Tunnel guarantees a stable and secure data exchange between OPC Client and Server, even through firewalls.

Softing’s S7/S5 OPC Server includes a redundancy feature for high-availability applications. The OPC Server has the capability to utilize two independent Ethernet connections (line redundancy—a primary and a secondary connection), to communicate to a PLC. The primary connection is constantly monitored, and in case of a failure the OPC Server is automatically switched to the secondary line within a single OPC cycle.

In addition, Softing’s S7/S5 OPC offering includes an industrial ActiveX OPC Client control that encapsulates OPC-related communications. Furthermore, the ActiveX control fits seamlessly into standard Microsoft software packages including Excel, Visual Basic, Microsoft Access, and Internet Explorer without additional runtime license fees.

Softing, a member of the European Steering Committee of the OPC Foundation and author of the OPC Book, actively contributes to the success of OPC by providing high quality OPC products, enabling their customers to stay in the forefront of the industrial communications technologies they deploy.