The PLC: a logical development

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Programmable Logic Controllers (PLCs) have been used to control industrial processes and equipment for over 40 years, having their first commercially recognised application in 1969. Since then there have been enormous changes in the design and application of PLCs, yet developments were evolutionary rather than radical. The flexibility of the PLC does not confine it to industrial use and it has been used for disparate non-industrial control application. This article reviews the history, development and industrial applications of the PLC.

The 1960s was a decade of intense technological development influenced by the political circumstances of the time; it was the height of the Cold War and the space-race and in the United Kingdom, Prime Minister Harold Wilson emphasised the role of technology in his famous "White Heat" speech. Sir Leon Bagrit, a leading industrialist, became chairman of Elliot Automation, a newly established company. Bagrit's BBC Reith lectures of 1964 on automation, encapsulated the industrial and technical ambitions of the time [1]. Automation was a hot topic and transistor electronics and computers were unfolding as significant technologies.

Technical Innovation in the 1960s: real-time computers for control

Bennett has given a succinct account of the historical development of computers for real-time control [2]. One of the key developments was Direct Digital Control (DDC), which used the computer to calculate control values and directly drive devices such as a control valve positioner. This Bennett calls the second phase; the first phase, prior to DDC, was supervisory control, where control settings are calculated by the computer and manually conveyed to the analogue control system.

The wider applications of computers in control for data acquisition, laboratory automation and factory automation tasks were increasingly recognised, but computers were expensive. The continued decrease in cost and size of electronic devices and small computers eventually led to the economic application of real-time control by computer [3].

Early alternatives to computer control

Arguably, programmable industrial automation first made its appearance in the 18th Century in the textile industry, when Jacques de Vaucanson designed a loom that was programmed to weave different patterns by the use of a drum with punched paper tape around it [4]. The late 19th and early 20th centuries saw the widespread use of electrical machines and with it, sequential control by means of drum sequencers and later sequential control using electro-mechanical relays and timers. Drum sequencers, similar in principle to music box movements, were programmed by positioning switches around a rotating drum. However, few designs could respond to plant conditions, so most supplied only sequential open loop control. The versatility of the electromagnetic relay enabled complex control schemes, which could include conditional responses, to be developed to a high level of sophistication. By the 1950s and 60s, relay-based control systems were widely employed in a variety of technical domains because of their simplicity and inherent reliability. Initially competition from semiconductor devices was limited since the relay could switch power levels and voltages well beyond the capability of semiconductors.

In relay-based control systems, the control sequences and conditional responses were determined by the wiring between the relays. Thus relay control schemes were re-programmed by altering the wiring. But in a manufacturing environment, a major disadvantage of this approach was that production had to be stopped to allow the circuits to be re-wired in situ. Next, the circuits needed to be tested both individually and in combination followed by the rectification of any faults that were discovered which could require further rewiring. All in all, this was a time consuming and expensive process.

Improvements came about from developments in electronic engineering, in particular the introduction of the transistor. By the late 1960s, inspired by the sequencing of computer instructions and transistor-based logic elements that could reproduce the functionality of relay circuits, solid-state electronic control systems using “plugboard” based programming techniques had been introduced for relatively small sequence control applications. There were perceived advantages in improved reliability, particularly when used in place of relays in environmentally challenging situations. Another significant advantage was that the control system could be modified by changing the connections on a “plug-board” with minimal downtime and engineering effort required to achieve control and sequence changes. This was a popular goal and one that earlier could only be fulfilled by larger and more expensive computer controlled systems, predominantly used by large organisations.

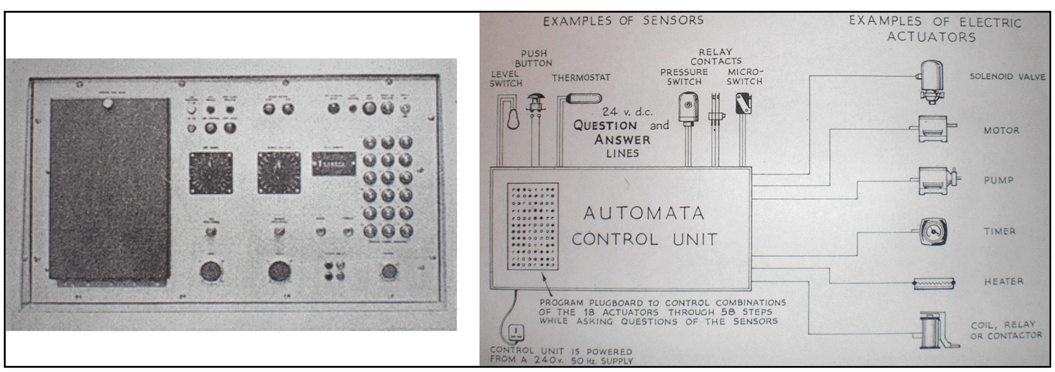

Fig 1. Automata System (From Hatherly [5])

Although limited by today’s standards, plug-board programmed electronic systems such as the “Automata” system [5], shown in fig 1 above, were seen as a logical advance from the fixed program functionality of relay based systems.

Programmable Logic Controllers

Initially developed as a relay-replacer, the early PLC was able to perform on-off control using programmable sequential and combinatorial logic and allowed plant technicians to alter the sequential logic without the need for re-wiring [6].

Another important feature of the PLC was that it did not require the complex computer programming skills found with the industrial computer applications of the time. The Modicon 084, for example, had a programming interface that was coded by rotary thumbwheel and simple on/off switches and a display comprising of lamps and numeric digit displays. In these early PLCs such as the Modicon 084 and Allen Bradley's Programmable Matrix Controller [7], the thumbwheel and on/off switches were directly connected (electrically) to the PLC logic circuits. This interface enabled the digital states depicted in electrical wiring diagrams (known as ladder diagrams) to be directly programmed via the programming device (fig 2). Ladder diagrams represented relay-based wiring in a form already familiar to electrical engineers and technicians, so, without extensive training, they could easily interpret and implement new designs and modifications.

Fig 2. Programmable Matrix Controller Programming Tool (From Scientific American [8])

Additionally, plant maintenance engineers and technicians understood the technology and its programming language, ensuring that the new PLC technology could be supported without requiring additional knowledge and expertise [9]. Later PLC programs were entered via a computer terminal, but with a few exceptions the ladder notation was retained and has been developed as a graphical programming language.

In the late 1970s and early 1980s, PLC designers took advantage of the rapid developments in electronic and microprocessor technologies to enhance PLC functionality. One of the key developments at this time was the ability to read-in and process analogue instrument signals.

Early analogue-to-digital converters (ADCs) employed electro-mechanical, electro-optical or electronic devices. Electro-mechanical devices, similar to the devices shown in fig 3, required the conversion of electrical signals into digital representations by the position of a rotating shaft, commonly achieved using a self-balancing bridge servomechanism [10]. Electronic ADCs were also used for high-speed conversion but were more expensive than servomechanism based systems.

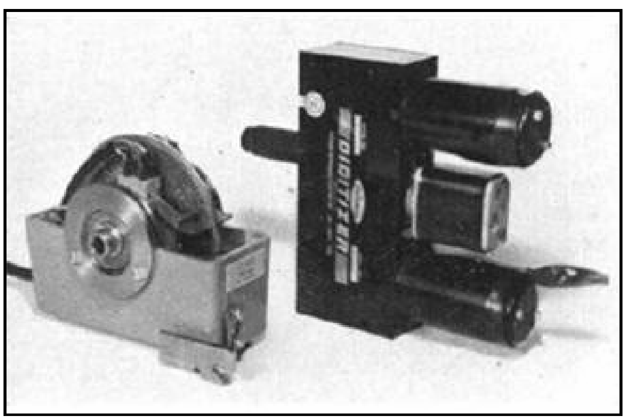

Fig 3. Giannini Shaft Encoder (left) and Coleman Shaft Decade Switch (right). (From Partos [10])

In closed loop configurations the accuracy of control is determined partly by the precision of the analogue inputs to the controller. Analogue outputs are within the control loop and do not demand such high precision. The critical component is therefore the analogue to digital converter, but high precision can be costly. One way of reducing costs was to share the expensive ADC circuitry between a number of inputs by multiplexing the input signals. Multiplexers like the "Uniselector Digitiser" shown in fig 4 below were costly but relatively inexpensive when compared to having one ADC circuit per channel. With increasingly viable analogue input and output interfaces and growing processing capabilities, the PLC was able to compete with analogue process control technologies such as single loop three-term controllers and Distributed Control Systems (DCS) used in the process industries [11].

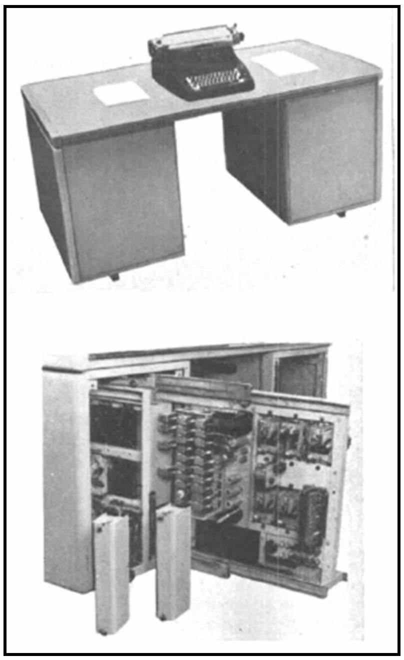

Fig 4. Elliot Brothers Ltd Uniselector Digitiser. Complete assembly (Top) and left assembly retracted (bottom). (From Partos [10])

Digital Communications

The PLC was originally designed as a single, dedicated control system working in isolation. One controller would be allocated to a single plant or machine under its control. However, this was limited to physically small areas because sensors, instrumentation and actuators needed to be individually and directly connected to the PLC. As electronic components became smaller and less expensive due to developments in transistor and integrated circuit technologies in the 1970s, it became feasible to locate individual ADCs on separate scattered items of controlled equipment; this reduced the potential for electrical interference that long cable runs carrying analogue signals could pick up, which could render centrally located PLCs on large sites impractical. The use of digital communications techniques enabled the processor to communicate with remotely located input and output systems by a single cable and to exploit error detection techniques. All this reduced the cost and complexity of handling large numbers of inputs and outputs over long distances.

Digital communication also enabled the PLC to exchange data with other computer systems providing connectivity with computer-based Human Machine Interfaces (HMIs) that replaced the early special purpose “mimic” panels. Further benefits allowed the PLC-based control system to communicate to higher level computer systems such as “Supervisory Control and Data Acquisition” (SCADA) systems, providing the means to distribute not only inputs and outputs but also control via early “fieldbus” technologies [12].

Several companies developed their own “proprietary” versions of the PLC, including their own brand of fieldbus communications, and the 1990s saw moves to standardise both the PLC, the programming languages used and the fieldbus based communications. However, standardisation has only been partially achieved. Known as the “Fieldbus Wars”, the attempts, to standardise control system communications through the IEC 61158 standard resulted in the present day array of no less than 18 different fieldbus systems, with particular industry sectors having a preference for their own protocol, heavily influenced by individual PLC manufacturers [13].

The definitive standard for PLC hardware, software and associated peripherals, IEC 61131, has had wider acceptance by both end-users and PLC manufacturers. However, despite common agreement on the definition of the programming language notation, the resulting programs are not portable – unlike programs produced for other fields, written in standardised high level programming languages. The PLC still requires the use of proprietary programming tools or software to write and load programs, but these can now be readily understood by most control and electrical engineers familiar with the IEC 61131 notation.

Applications of PLCs

The selection and application of control technologies, particularly PLCs, vary considerably between different industry sectors. As part of a research programme, senior engineers from four industry sectors were interviewed to shed light on the differences in PLC application. The four sectors – steel, petrochemical, agro-chemical (batch) and discrete manufacturing – were chosen because they are representative of the main types of manufacturing. Broadly speaking these can be divided into two main groups: process and discrete. In process manufacturing, the product is generally undifferentiated except for batches, for example petrol and chemical products. Discrete manufacturing is the manufacturing of individual or series of separate units where one product can be differentiated from another, and examples range from one-off bespoke complex machines (for instance, oil rigs or special purpose machinery for packaging systems) to the manufacture of cars or tins of baked beans produced on fast moving production lines.

Steel industry

The production of steel inevitably produces a severe environment for any control system. Particular consideration has to be given to the harsh environmental conditions such as high ambient temperatures, potential dust ingress, vibration and electrical noise. The PLC in particular has been designed by manufacturers familiar with the demands of these working environments, consequently one of its main characteristics is robustness. The PLC commonly achieves this because it has no moving parts and it does not require additional cooling systems such as fans. PLC components are generally of a higher specification in terms of operating temperature and vibration tolerance and the PLC is designed to interface with the equipment and instrumentation located on the plant.

One of the drawbacks of the early PLC was that all sensors and actuators had to be connected directly to the input and output (I/O) channels of the Central Processing Unit (CPU). Locating a PLC centrally resulted in long and complex cable runs prone to pick up electrical noise from the heavy electrically driven machinery common in the steel industry. The introduction of remote I/O placed near the individual units under control and communicating digitally with the PLC's CPU via a single cable reduced problems of interference. However, remote I/O introduced another problem, that of response speed.

David Young (interviewed on 19/09/07) described his early experience of a PLC based control using distributed inputs for rolling mill positioning control. The problem was identified as the time taken to transmit position measurement data back to the PLC, process the signal and then send a response to set an actuator. In essence, the scan time of the remote I/O was found to be too slow to allow a timely control action to stop a 10 ton steel sheet at the right point without overshooting its target.

The solution reduced the communication latency by locating an additional small PLC close to the machine that could receive data and control the process directly without the need to wait for a response from the central PLC. This main controlling PLC was then just transmitting and receiving time independent data and not directly controlling the process. This approach increased the opportunities to exploit PLCs in large plants, particularly those covering physically large areas.

Thus, in the steel industry, passive and intelligent remote I/O and PLCs allowed the connection of remote sensors to a single master PLC via a digital connection which reliably transmitted the signals without degradation over large distances. Digital communications enabled PLCs to interface with existing control and instrumentation systems and co-ordinate independently controlled smaller areas of plant or clusters of machinery [14].

The Process Industries

In process industries, such as agro-chemical, there are commonly many process parameters to control and hence large numbers of analogue instruments measuring parameters such as temperature, flow and pressure with their associated control loops. With such stress placed on analogue instruments and controls, the Distributed Control System (DCS) has been the preferred form of control system, typically employing large mainframe computers situated in a centralised instrumentation and control zone [6].

Emphasis is on the control of process repeatability and stability. Bound by strict quality control regimes, regulation and hazardous processes, the process industry tends to be conservative. David Leeming (interviewed on 30/05/08) explained that PLCs are employed on process plants but usually for “packages”, ancillary equipment with fixed functions such as compressors, air conditioning systems, pumping stations and so on. Packages provide a service to the main plant and are fixed in function and output. There is usually no requirement to alter their operating parameters and it has become common practice for the package equipment supplier or sub-contractor to provide the maintenance and expertise for a package allowing the plant operator’s engineering staff to concentrate on the management and control of the process itself. Thus process engineers, operators, and technicians are primarily concerned with the core function of the plant, which is to make the product consistently and reliably.

Process controls, therefore, have to accommodate quality fluctuations caused by feedstock variations. On a medium to large processing plant (occupying large physical areas) having data readily available in a central location means that with suitable communication links, remotely located departments for quality and process control can examine this data and modify process parameters without having to enter the plant or control room. Considerable emphasis is therefore placed on data acquisition systems, providing another reason why the DCS is the preferred control technology since they are designed to handle complex control algorithms and are capable of sharing and presenting plant data on standard computer platforms [15].

A common feature of many chemical plants is the processing of hazardous chemicals entailing strict regulation and safety control systems. The centralisation and marshalling of the instrumentation connections in one location aids the management of such systems, particularly if an intrinsically safe design is required. A single control room simplifies co-ordination of the plant's operation, provides a clearly defined zone where control changes can be made and supports access control. Within such an environment, there is a reluctance to change from well proven systems.

Petro-chemical plants are in many ways similar to other large and medium scale chemical plants. There is, for instance, an emphasis on safety, particularly with a concern over explosive atmospheres. However there are some key differences in approaches to the use of control technologies in the petrochemical field and other industries such as in the water and waste water treatment where there is a greater acceptance of PLC technologies because the processes are more repeatable and less variable. Overall control can be achieved by remote Supervisory Control and Data Acquisition (SCADA) systems linking many distributed PLC systems [16].

Plants in these industries also cover large geographical areas, resulting in the requirement for remote and unmanned operation of the plant. Additionally, raw materials and processed products are transported over great distances via pipelines. Pumping and valve stations need to work autonomously with minimal remote supervision. The PLC lends itself very well to these remote applications due to its reliability, robustness and communications capability.

A common feature of the process industry sector is a preference for keeping systems simple. Many advances in PLC technology have been met with scepticism from engineers. Alan

Morris (interviewed on 30/11/07) claims that “the PLC has tried to become too flexible” and “all things to all men” which may provide the basis of an explanation as to why PLCs are relegated to “packages” and simple automated task control in many process industry applications.

Discrete manufacturing

High-volume discrete manufacturing is repetitive and often organised as an assembly line where a sequence of operations is performed. An automotive assembly line for example builds a vehicle via a combination of sequentially controlled steps from a set of parts. Each vehicle can be uniquely identified but is similar to the previous vehicle on the production line. The assembly process can be broken down into actions, which when combined in a prescribed order construct each finished vehicle. This type of process can be readily controlled by one or more PLCs. A benefit of using the PLC is that engineers and technicians can easily modify the sequence and logic of the PLC to accommodate production line changes.

Bespoke machine manufacturers, equipment suppliers and systems integrators (the organisation or person that supplies the control system software and design skills) also benefit from the flexibility that a PLC can bring through its high level of configurability, especially where one-off special purpose machines are constructed from commonly used parts. A PLC can be adapted to different configurations of machinery to meet the requirements of different clients through a familiar programming interface. Developments such as analogue inputs and outputs plus mathematical processing have increased the functionality of the PLC so all aspects of machine control can be controlled by one system.

Peter Bruce (interviewed on 18/01/08) explains that early developments entailed connectivity with larger micro-computers such as the Digital Equipment’s PDP-11. Now connectivity to the personal computer (PC) is the norm and extensive graphical displays and data manipulation is possible. In the larger process industries, this would normally be achieved through SCADA or DCS but many machine builders program their own HMIs to reduce costs.

Conclusion

Computers monitored and controlled manufacturing processes from the 1950s. Initially employed to log and analyse plant information, it was not until the development of direct digital control (DDC) in the 1960s that digital computers were capable enough to automate plant operation fully and close the control loop. Initially, early computing effort in control concentrated on large plants where the high levels of investment could be justified. Developments in electronic technologies improved reliability, reduced physical size and cost and encouraged the development by the end of the 1960s and early 1970s of a simple form of computer constructed specifically for control applications in the guise of the programmable controller, later to become known as the PLC. The new system was designed to work in real-time, interface with sensors and actuators and allow control engineers, electrical engineers and technicians to learn quickly and apply the PLC as a replacement or supplement to relay based control systems.

The first PLCs provided on-off control and the succeeding analogue-capable PLCs were limited in their ability to process analogue signals. By the 1970s and 80s, developments in microprocessors were readily adopted by PLC manufacturers and improvements in the PLC's capability allowed it to perform complex control algorithms. Distributed control architectures became feasible with the adoption of digital communication. By the 1990s, PLCs were widely used for control applications throughout industry and beyond and partially successful attempts were made to standardise the disparate aspects of PLC technologies.

Among the industrial sectors of process, steel and discrete manufacturing the application of PLC technology differs. Where analogue measurement and control parameters are dominant, such as the process industry, the DCS is the primary control system used; PLCs are secondary and mainly integrated into OEM packages. Where combinatorial and sequential control dominates, PLCs can be found in abundance.

It should be noted that the PLC is not just confined to manufacturing applications. PLCs can also be found controlling ships systems and engines, car washes, lock gates and even fairground rides. However, it is not a general purpose computer designed to run a multitude of different software applications like the PC but is dedicated to perform explicit control tasks. The PLC, although highly configurable, is a specialised tool, designed to run just one program and tailored to suit the control task in hand.

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