Application and Development of Fieldbus

Executive Summary

by

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Abstract

Confusion over fieldbus technology by manufacturers and customers alike is due to a number of factors. The goal of a single global fieldbus standard, the subsequent development of European standards, the recognition of a number of emerging de facto standards and the continued international standardisation of fieldbus technology is still perplexing potential fieldbus users. The initial low supply and demand for suitable devices and compatible controller interfaces, the high cost of control systems and inertia caused by resistance to change have all contributed to the slow adoption of fieldbus technology by industry. The variable quality of fieldbus documentation has not assisted the acceptance of this new technology.

An overview of industrial control systems, fieldbus technology, present and future trends is given. The quantifiable benefits of fieldbus are identified in the assessment of fieldbus applications and guidance on the appropriate criteria for the evaluation and selection of fieldbus are presented. End users can use this and network planning to establish the viability, suitability and benefits of various control system architectures and configurations prior to implementation.

The enhancements to a network configuration tool are shown to aid control system programming and the provision of comprehensive diagnostics. A guide to fieldbus documentation enables manufacturers to produce clear, consistent fieldbus documentation. The safety-related features for a machine safety fieldbus are also determined for an existing network technology.

Demonstrators have been produced to show the novel use of fieldbus technology in different areas. Transitory connections are utilised to reduce complexity and increase functionality. A machine safety fieldbus is evaluated in the first installation of a fully networked control application. Interoperability of devices from many different manufacturers and the benefits of fieldbus are proven.

Experience gained during the membership of the British Standards Institution AMT/7 Committee identified the impact of standards and legislation on fieldbus implementation and highlighted the flawed use of standards to promote fieldbus technology. The Committee prepared a Guide to the evaluation of fieldbus specifications, a forthcoming publication by the BSI.

The Projects presented have increased and developed the appropriate use of fieldbus technology through novel application, technical enhancement, demonstration and knowledge dissemination.

Acknowledgements

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Thank you Jackie for your support, endurance, patience and marvellous sense of humour, when it must have been very necessary.

Finally, thank you to my family, especially Gillian.

Declaration

The work presented has been undertaken by myself unless otherwise acknowledged. Apart from the submission for the Degree of Master of Science in Engineering Business Management, this work has not been previously submitted for any other award.

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1 Introduction

1.1 Fieldbus

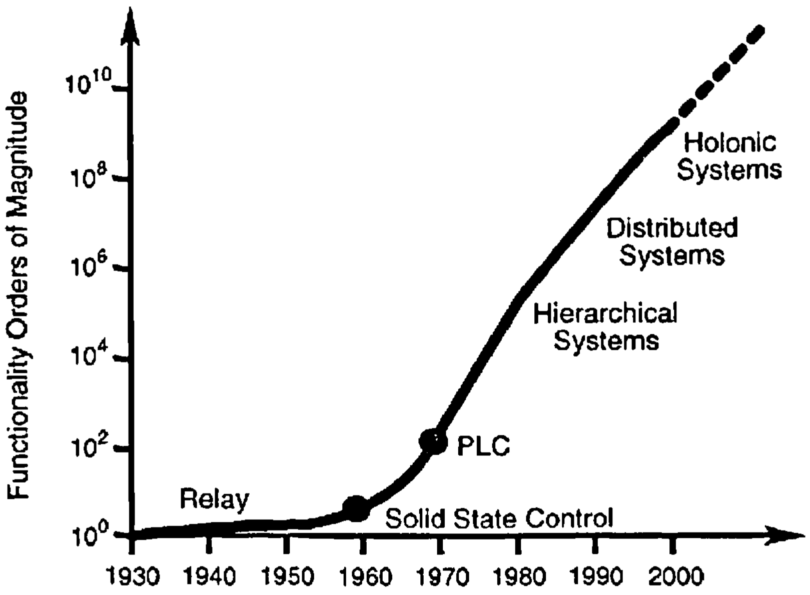
Fieldbus is defined by the International Electrotechnical Commission (IEC) as a "generic term for a serial, digital communications network, supporting multiple measurement, control and actuation devices on a shared medium."[1] The term fieldbus is commonly used in the automation industry to describe non-proprietary or open network technologies. The fieldbus industry is still very young, with the initial take up of the technology being slow, particularly in the UK.[2,3] Recently, rapid growth has been reported by fieldbus associations and in market surveys.[4,5] Fieldbus networks are increasingly replacing the traditional hardwiring of automation systems, with manufacturers using fieldbus as a core strategy in the provision of seamless control system integration.[6,7] Fieldbus technology presents many strategic benefits, however with a low rate of adoption in the UK, these opportunities are being missed. The project objectives were to increase and develop the appropriate use of fieldbus technology.

1.1 Control system & fieldbus history

Prior to 1969 traditional machine control was based on Relay Control Systems.[8] The high cost of modification and revision to control systems for each new model prompted General Motors to specify solid state (semiconductor) control systems. This was to provide the same functionality as Relay Control Systems providing logic capability improved reliability and expansion.

Other requirements included competitive pricing with relay panels, ease of programming (hence relay ladder logic), modularity (to facilitate fault-finding and repair) and compactness. The controller also had to be rugged, operating in an industrial environment and easily interfaced with existing input and output devices. The final consideration was maintenance, to be undertaken by the same electricians looking after the current systems.

In response to this the programmable logic controller (PLC) was developed in the early 1970s, operating with the sensing and output devices in a similar manner to relay control, with field wiring still providing electrical inputs and outputs to and from the control panel respectively (Figure 1).



Source: Allen Bradley

Figure 1 Control technology development

Shortly afterwards the first device network was introduced by Cutler-Hammer called Directrol, but the features were too advanced for the PLCs and PCs available at the time and the network disappeared in the early 1980s. The intervening period saw most control system manufacturers produce proprietary remote I/O networking solutions, replacing the hardwiring of sensors, actuators and other I/O devices back to local PLCs or remote PLC I/O racks. In addition to these, there are specialist networks for many applications, including motion control, welding and hazardous environments.

In the 1990s control systems manufacturers were compelled by market pressure to open previously proprietary networks (e.g. AS-i, ControlNet, DeviceNet, Interbus, Profibus, & SDS). The degree of openness can be distinguished by the number of supporting manufacturers and the technology association management (some are still closely managed by the companies that developed the technology). Since the mid 1980s there have been efforts to produce an international universal fieldbus standard, that was originally more suited to the process industry (recent developments indicate this standard may combine a number of yet undecided incompatible technologies). Differences between technology consortia caused a proliferation of standards activity in the mid 1990s to market open fieldbus technologies and gain competitive advantage. This resulted in three European standards, two comprising a number of incompatible technologies, with more European and International standards in progress.[9]

1.2 Industrial market situation

At the outset of this research there was very low market penetration of fieldbus technology in the UK. Barriers have slowed the implementation of fieldbus technology (Figure 2).

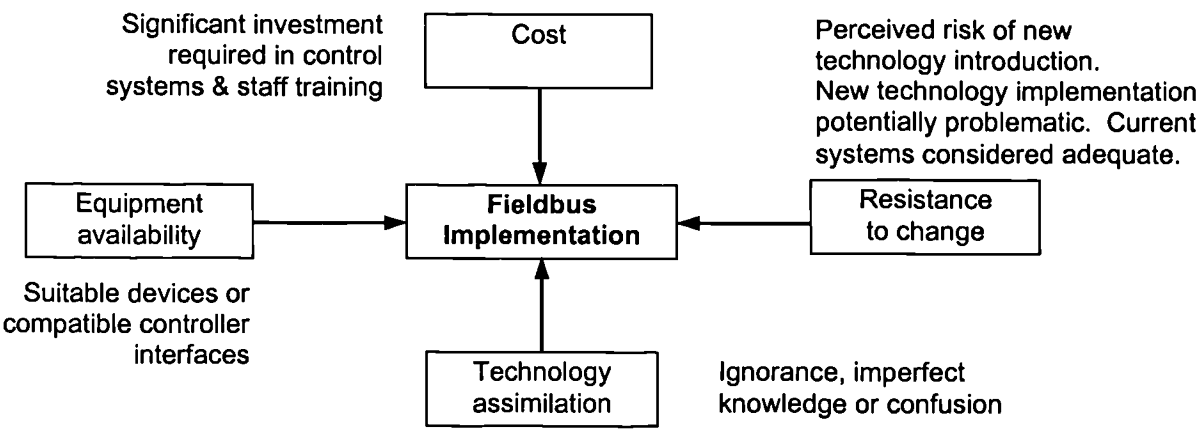


Figure 2 Barriers to fieldbus implementation

The investment required when changing or upgrading control systems has influenced buying decisions, particularly where small companies are concerned. Many of the early large-scale fieldbus installations have been in large companies that can afford to devote significant resources to automation.[10] Companies with a stable or falling demand are unlikely to make additional investment, unless it can reverse the anticipated market demand.

Availability of fieldbus equipment has been a problem during the introduction of fieldbus. Many device manufacturers were slow to develop fieldbus interfaces due to low demand and market confusion. Manufacturers have in some cases only produced fieldbus versions after education by customers. Interface development is still viewed by some as cost that may not be recouped in the foreseeable future, but the only means to keep important customers. Limited equipment availability affected users in two ways, in the suitability of interfaces to existing equipment and the need for specific field devices for applications. This then created either a time lag in implementation or additional cost issues. Fieldbus continues to be viewed as a remote I/O replacement, as opposed to a means of transparent integration of intelligent devices.

The market was ignorant of fieldbus, in an effort to inform UK industry the DTI produced a fieldbus guide, unfortunately biased more towards process industries than manufacturing.[11] The Department of Trade and Industry (DTI) is currently sponsoring the FACES (Fieldbus Awareness Campaign and Exploitation Support) programme to promote awareness and benefits of the technology. DTI have also partially funded the forthcoming publication of a guide to evaluation of fieldbus, produced by the British Standards Institution (BSI).[12]

Confusion and misunderstanding are still common amongst those that are at least aware of fieldbus. The number of different technologies available confuses potential users, but manufacturers and fieldbus organisations are marketing the strengths and the almost universal suitability of each technology to any potential application.

This situation has been exacerbated by the strategy of some producers to seek standardisation of their technology to ensure market penetration through the competitive advantage obtained. As a result, the implementation of fieldbus has been slow. Many potential users are waiting, anticipating market consolidation with fewer technologies or hoping for a universal fieldbus solution.

Inertia can also be attributed to a resistance to change, exhibited by the unwillingness of some control engineers to use fieldbus. Reasons given demonstrate perceived risk in the application of new technology, which may be unproven, even in a particular industrial sector. This view seeks to lessen and delay the 'learning curve' where the implementation could be time-consuming, painful and expensive.[13] The painful aspect of fieldbus continues to be felt by engineers in the selection of a particular fieldbus in an environment where there are many potential solutions and little educated advice. Figure 3 shows the adoption cycle of new technology, sometimes beginning with a state of euphoria, where the technology is regarded as a panacea. This is followed by a negative reaction (rapidly becoming cynicism) as the limitation and potential of the technology is known. Over time the technology is understood and used appropriately. The slow acceptance of fieldbus technology in the UK indicates that control system engineers do not harbour feelings of euphoria over new technology. Instead treating new technology at the outset with what is often regarded as healthy cynicism. Followed by gradual acceptance, preferably after someone else has proved it.

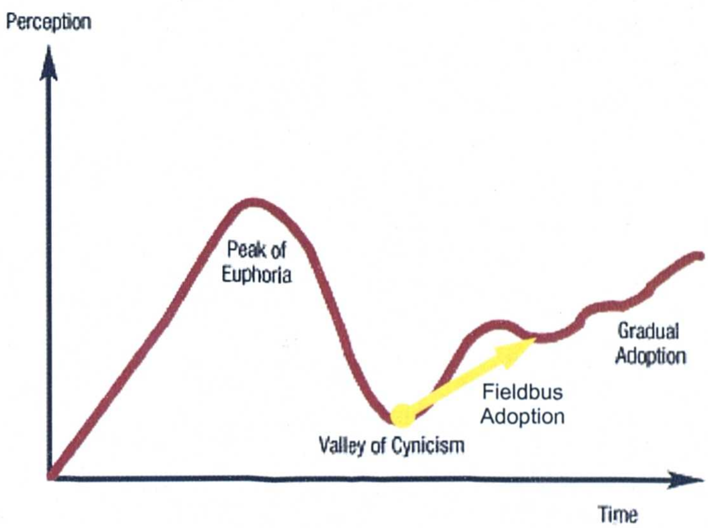


Figure 3 Adoption of technology cycle diagram

Source: After Rockwell International Corporation

Many manufacturers could now be approaching the peak of euphoria, attempting to supply many different network interfaces, prior to rationalising in the face of market confusion and impending fieldbus consolidation. When the real UK market perception is beginning to rise out of the valley of cynicism.

1.3 Portfolio overview

In order to address these problems a number of projects have been performed covering different aspects of fieldbus implementation. Unbiased guidance on selection and the application of fieldbus technology is given, and new applications of fieldbus technology are developed.

Projects presented are:

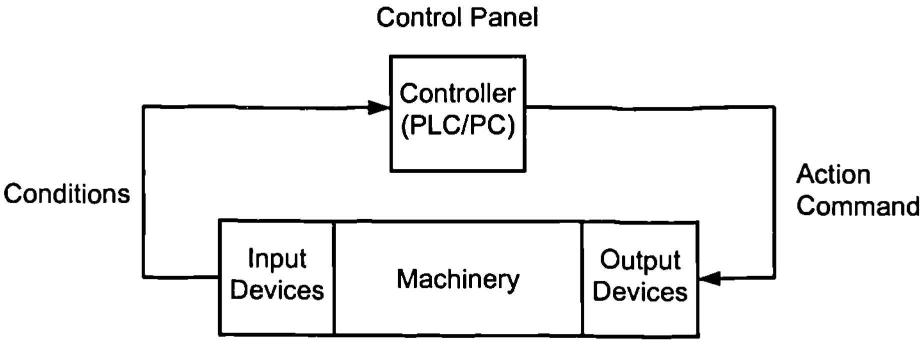
1. Selection of fieldbus technology, network planning, configuration tool and device manual enhancement.
2. Equipment integrated into fieldbus demonstrator to show interoperability of devices, features and benefits of fieldbus technology.
3. Application case studies illustrating quantifiable benefits and advantages of fieldbus.
4. Transitory fieldbus connection for robot tool changer and safety devices.
5. Impact of fieldbus standards and legislation, participation in the British Standards Institution (BSI) Advanced Manufacturing Technology (AMT/7) Committee (fieldbus) & preparation of BSI fieldbus guide.
6. First installation of an integrated safety fieldbus solution and research into additional safety related features required for a fieldbus to meet machine safety standards.

These projects are discussed following an overview of fieldbus technology.

2 Fieldbus overview

2.1 Control systems

A programmable logic controller (PLC) or personnel computer (PC) may be used to control a process (Figure 4).



Source: After Allen-Bradley

Figure 4 Machine control

Traditionally, the input devices and output devices are hardwired to the controller. Typical industrial input/output devices are shown in Table 1.

Input Devices	Output Devices
• Limit, proximity, pressure, and temperature switches • Push buttons • Logic • Digital data • Analogue (flow, pressure, speed, temperature, etc.)	• Solenoids • Motor starters • Indicators • Alarms • Logic • Digital data • Analogue (flow, pressure, speed, temperature, etc.)

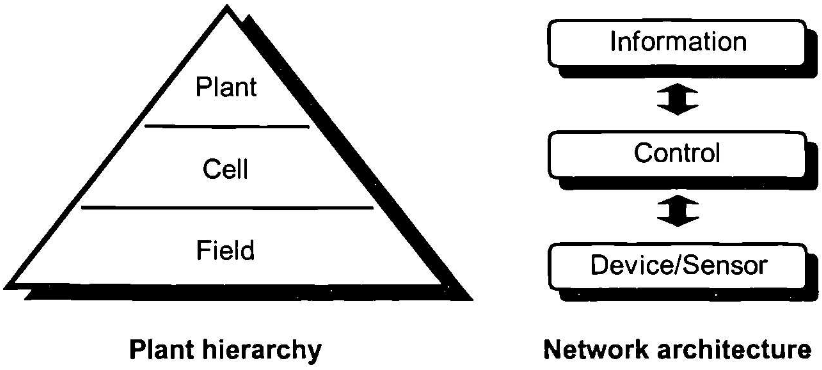
Source: After Allen-Bradley

Table 1 Industrial input/output devices

A fieldbus is an alternative to individually wiring inputs and outputs, however other data may also be passed between the controller and field devices. These may include device configuration data, diagnostic data, robot programs and process data.

2.2 The fieldbus solution

Automation manufacturers offer integrated plant control systems that correspond to the automation pyramid paradigm, with fieldbus networks providing the communication strategy enabling total and seamless integration (Figure 5).



Source: Siemens & Allen-Bradley

Figure 5 Plant communications heirarchy

This communication architecture may be utilised as the control system strategy, the example shown in Figure 6, is the network architecture used in the Structurally Advanced Light Weight Vehicle Objective (SALVO) project at the Warwick Manufacturing Group.

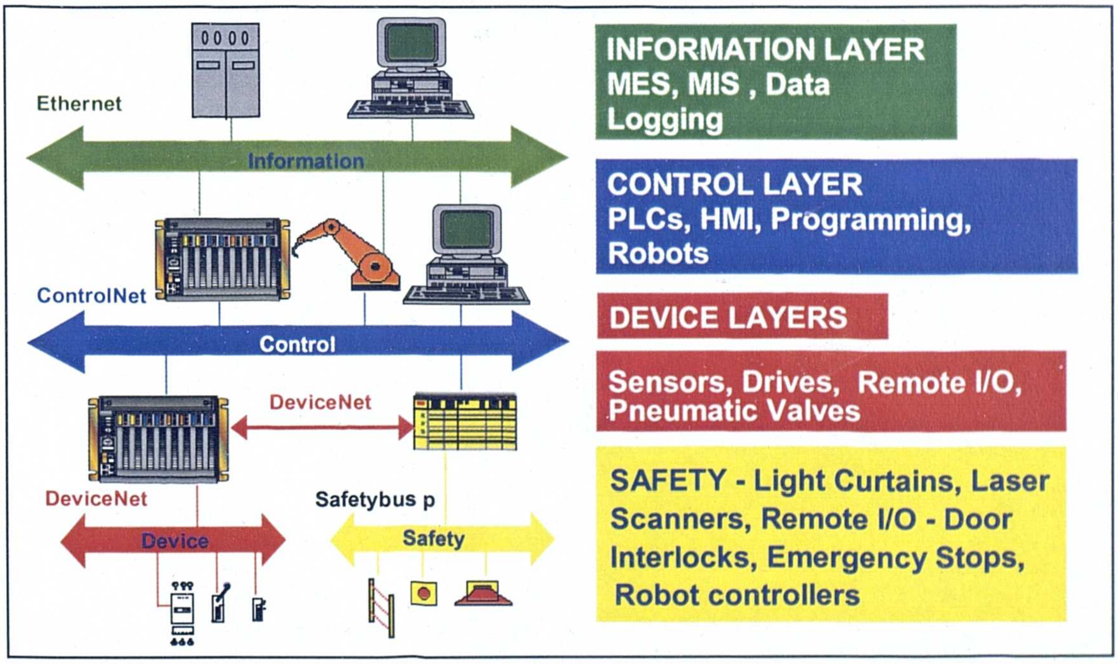


Figure 6 Control & network strategy

The distinct requirements of each layer necessitate the provision of different fieldbus technologies (Table 2). The characteristics of the different networks balance the need for real time control (time critical), with little data, against a less timely response (non-time critical) with large quantities of data. The control layer can support a mixture of time critical and non-time critical data, such as I/O data, operator displays, motion control, and the downloading of device configuration data and program data (e.g. robots & PLCs).

Layer	**Network size**	**Data volume**	**Response time**
Information	Large	Large	Slow
Control	Moderate	Moderate	Moderate
Device	Small	Small	Fast

Source: Soo Beng Khoh[14]

Table 2 Network characteristics

2.3 Strategic benefits of fieldbus

According to Fieldbus standard IEC 61158 (approaching completion) fieldbus users can expect the following strategic benefits:[15]

- reduction in capital cost to build or expand plant;
- faster commissioning or refits of plant;
- "more product with less material";
- improved, closer, more flexible and repeatable control;
- greater precision and accuracy;
- reduced maintenance and running costs;
- global practice and sourcing;
- improved safety and integrity of operations.

2.4 The automation industry & fieldbus

The high cost of automation is illustrated by the £6.5 million investment in a new assembly line by Ford at the Halewood Transmission Plant. The gearbox assembly line was previously traditionally hardwired and complex, with 200 cable terminations in a typical control cabinet. This made the line difficult to set up, maintain and change, where the competitive environment necessitated increased capacity and better quality with reduced cost.[16]

The Ford manufacturing engineer stated that the complexity of the old control system caused problems to be time consuming to locate and expensive to rectify. These concerns led to the implementation of fieldbus technology, enabling improved responsiveness to quality and cost trends, (through better data management) with increased flexibility and maintainability.

2.5 Case studies – principal benefits achieved

The main benefits highlighted by end users have been in system commissioning, diagnostics, maintenance, design and increased flexibility. Cost and time savings in most cases have been very significant. Diagnostics has been frequently quoted as important, but implementation of the full capabilities has not always occurred when a system is initially installed. This was found in some cases to be due to the retraining of staff and pressures to complete the work to meet production schedules.[17,18]

3 Selection of fieldbus technology & network planning

3.1 The fieldbus market

System integrators, Original Equipment Manufacturers (OEMs) and end users had expressed their confusion over the choice of fieldbus for particular applications. This can be illustrated by the choice shown in Figure 7, of small number of the leading open technologies.

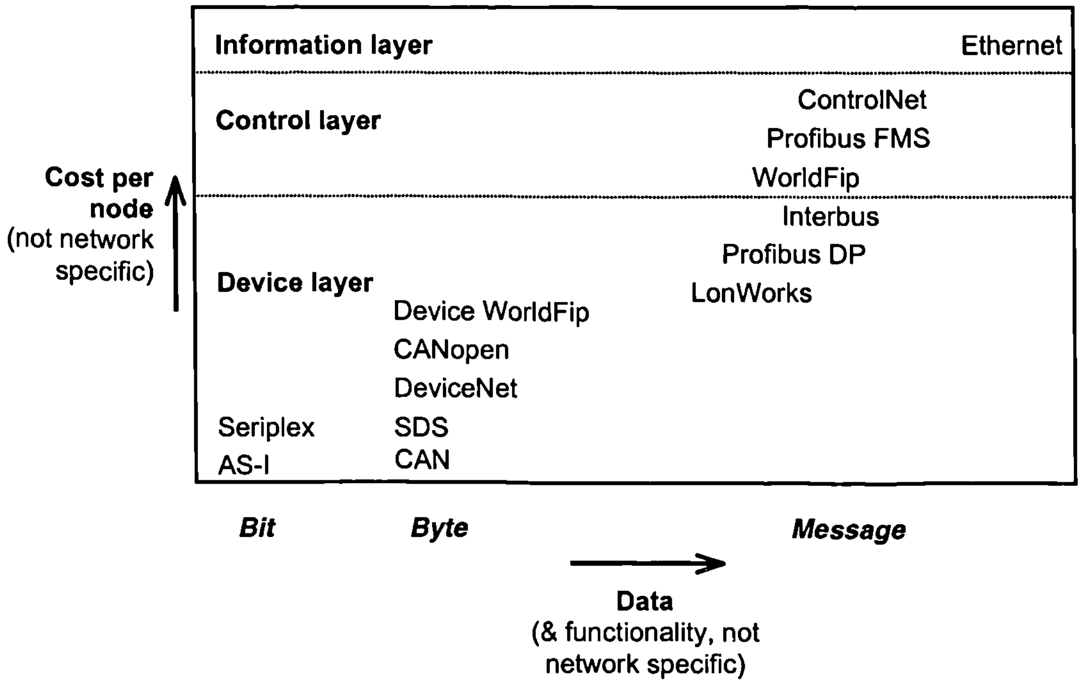
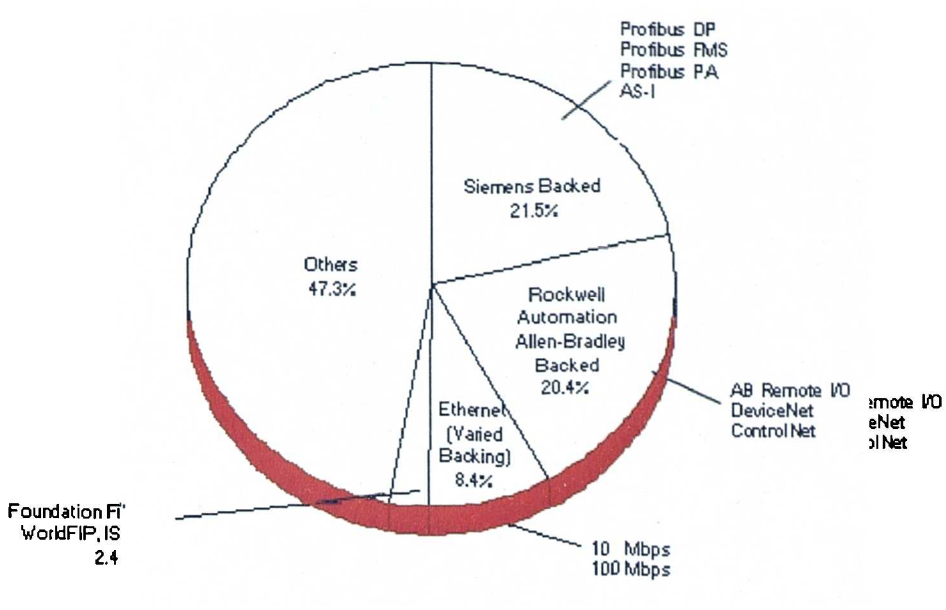


Figure 7 Network positioning of leading open fieldbus

The major automation manufacturers' promote their now open fieldbus technologies as universal solutions for most applications, the user merely faces the choice of suitable network(s) for a particular application from those offered. The choice becomes more complex where device suppliers support multiple networks, backed by different major manufacturers, often offering virtually any fieldbus currently available (Figure 8).

This situation requires the education of potential fieldbus implementers, therefore it was necessary to establish unbiased selection criteria and then disseminate this information.[19]



1998 Total: $1.9 Billion (percent of Dollar volumes, products by network interfaces type, grouped by major backers)

Source: Venture Development Corporation

Figure 8 Worldwide shipment shares of distributed/remote I/O

3.2 Selection of fieldbus technology

The initial step is to understand the type of application (whether continuous, batch or discrete)[20] and how the differing requirements will affect the choice of fieldbus and devices. The company control system strategy could affect the network architecture, either through the choice of controller (PLC/PC) or a preferred controller vendor. It then follows that a decision must be made to use open or proprietary networks supported by the controller vendor.

The choice between open or proprietary networks gives the option of the best of breed products from many suppliers or the security of a single source solution. Open fieldbus associations must therefore ensure that products from multiple manufacturers operate correctly by conducting composite testing (physical layer, protocol compliance and device interoperability). Open fieldbus associations offer a means to check the availability of equipment and continued development of a technology.

Finally, technical features of the fieldbus should be considered. These are cabling (maximum length, device power option, connectors, media supported and topology), bridges/gateways, redundancy (controller and cabling), ability to swap devices under power, transmission of non-time critical data (e.g. device configuration) and time critical data throughput (to meet applications requirements).

Many potential users of fieldbus technology stress the real time nature of their applications and how this can be achieved with different fieldbus, often mistakenly comparing the raw bit transmission speed across the network. The importance of protocol efficiency, comprising of the message overhead (any additional information other than the required data) and the network model, must not be overlooked. The particular network model used will also affect the ability of the technology to support future technical advances (such as highly distributed control). Hence the use of the peer to peer network model in newer technologies (including DeviceNet, ControlNet and Fieldbus Foundation) as opposed to the source-destination model.

The innovative aspect of this work is the development by the author, of a basis for fieldbus selection by the evaluation of appropriate criteria. The work has been widely disseminated though the presentation of material at national and international conferences and on the Automation & Robotics Engineering Business Management MSc module.[21,22] Selection advice has also been given to companies visiting the Warwick fieldbus demonstrator, these have included BMW, Cadbury, Compaq, Ford, GlaxoWellcome, Gillette, Honda, Jacobs Suchard, Marley Building Materials, Mitsubishi, Nestle, Rover, Seven Trent Water and Thames Water. This work has been utilised by companies in the choice of appropriate networking solutions for their applications.

3.3 Network planning & installation cost comparison

Network planning of customer sites has been required where customers were considering the use of the DeviceNet fieldbus, but are not familiar with the technology. The potential DeviceNet installation was agreed with the customer and analysed to provide a comparison between different control system architectures.[23]

The researh engineer performed a spreadsheet analysis in order to estimate incremental labour and material costs for hardwire, proprietary network and DeviceNet installations. The installation cost of each architecture is calculated, allowing for the different controller interfaces, I/O hardware, cabling, trunking and enclosures. This was the first trial of Rockwell Automation US customer support software in Europe. The figures used in the calculations of rework, labour and material costs were therefore modified by the author to meet local expectations. Standard DeviceNet interface costs and hardwire device equivalents have been identified, incorporated in the spreadsheet and used in calculations. These were necessary to enable Rockwell Automation sales engineers and customers to apply the spreadsheet in a consistent and reliable manner.

The installed cost analysis required the network layout to be planned by the customer, often this had not done. Where the customer did not provide the required information, the necessary detailed planning of networks was found to be time consuming. A questionnaire has been developed to give customers an understanding of DeviceNet and the data requirements for the installation comparison, to encourage suitable data preparation prior to site visits.

The network data required for the spreadsheet calculation necessitated the estimation of cable lengths to each network device (from the programmable controller) and a measure of conventional wiring complexity (device wiring equivalent, necessary for the traditional direct wiring comparison where each device is directly wired to the controller). Labour, material and rework costs were agreed with the customer and revised if required. This practice increased customer confidence, particularly where the conventional direct wiring or legacy network installation costs were accurate when compared to existing installations. The DeviceNet network installation cost estimations were then seen as being realistic, even without prior knowledge of the technology.

The additional guidance given on device wire equivalence, and spreadsheet data requirements has assisted sales engineers and customers in the use of the tool. Case study evidence has shown that the revised labour, materials and rework costs can provide an accurate estimation for cost comparison between the three different control system architectures.

Company staff have been given formal training consisting of presentations, sample exercises and guidance when visiting customers. This has given Rockwell Automation customers the ability to question the viability, suitability and benefits of various control system architectures and configurations prior to implementation.

3.4 Configuration tool enhancement

There are different network configuration tools available for DeviceNet, however, the choice is presently dependent on the chosen controller. Device parameters and configurable options are described using device specific Electronic Data Sheets (EDS), independent of the configuration tool used.[24] The EDS enables device parameters to be altered (within legal values) by a user with the aid of help text. However, the EDS does not present the user with sufficient information to operate a device once it has been configured.

The user must determine the data required to control and monitor a device. The research engineer proposed the addition of a data and diagnostic sections to the EDS to facilitate device integration and programming.[25] A method is given to describe and identify the data mapping format required by a control system integrator and subsequently use this information in the configuration and programming of a device. Diagnostic text is then associated with the data mapping to provide predefined diagnostic messages corresponding to data produced by the device.

The DeviceNet electronic data sheet could be further enhanced to include standard blocks of program code, since device specific code is likely to be very similar. For example, whatever the actual application of a variable speed drive, it is necessary to check the status of a drive (no faults) prior to operation, then specify the speed and direction of rotation, whilst monitoring input data for correct operation. The code could be described within the EDS in an IEC 1131-3 (international standard for programmable logic controllers) language or by neutral means with Extensible Markup Language (XML), and subsequently imported into a programming tool or downloaded to a device. Many manufacturers claim compliance to IEC 1131-3 for their PLCs, however this does not indicate PLC programs for one brand of PLC will operate on another. The use of XML by a number of international standards committees (including ISO 15745 Open systems application frameworks and IEC 1499 Function blocks for industrial measurement and control systems) indicates the future direction for textual specification of engineering and configuration information.

The innovation of this project concerns the addition of EDS user data and user diagnostic sections to the EDS file structure. These additions will enable a user to identify device data and utilise or alter predefined diagnostic messaging. The end user or system integrator will have immediate access to comprehensive diagnostics which, would previously need to be individually programmed. This work is under review by Rockwell Automation, prior to submission to the Open DeviceNet Vendor Association (ODVA) System Special Interest Group (SIG), who manages the development of the DeviceNet EDS.

3.5 Manual design

The networking sections of DeviceNet manuals from different manufacturers are of variable quality. Experience gained by the author from the integration of devices on the fieldbus demonstrator and from observations made by end users has led to the development of best practice guidelines.[26] In the manufacturing industry, the use of networking technology in place of traditional methods has been likened to the replacement of relay logic with programmable logic controllers (PLCs).[27] Since many users are likely to be unfamiliar with the technology, it is necessary to provide suitable supporting documentation.[28] The DeviceNet manual design paper outlines, with examples, the information required by end users or system integrators.

The following information is recommend for inclusion in DeviceNet manuals:

- DeviceNet overview (key characteristics e.g. Device level network, CAN based, IPR owned by ODVA & ODVA contact details for further information).
- Example schematic network layout.
- DeviceNet network topology/cabling options (thick, thin & flat cable & current limits).
- Distance/baud rate options (trunk & drop cable lengths vary with baud rate & media type).
- Device configuration (Dip switch/settings software settings).
- Device/network diagnostics (DeviceNet module & network status LEDs).
- Device I/O data format/mapping (include diagnostics & alternative configuration options).
- ODVA device profile fault codes (DeviceNet Specifications Volume II).
- Manufacturer specific fault codes.
- DeviceNet communication supported message types, class services & objects (appendix).
- Printed version of EDS /electronic version of EDS on floppy disk (an EDS is required for device configuration, a printed copy of the EDS contents is only suitable for simple devices).

Where other documentation on network configuration is supplied or the simplicity of the device does not warrant more than a small leaflet, then the minimum information to be included in a device manual is recommended.

This provides a guide to the provision of high quality, consistent, DeviceNet documentation that can be easily understood by the end user/system integrator. Thus ensuring information that is required by DeviceNet implementers is not inadvertently omitted. It is under review by Rockwell, prior to submission to the Open DeviceNet Vendor Association.

4 Fieldbus application case studies & benefits

4.1 Background

The initial slow market implementation of fieldbus indicated that many potential users were not aware of the advantages the technology offers. Fieldbus organisations have claimed a number of benefits that may be obtained through fieldbus, however these were anticipated benefits based on information relating to the process industry, not manufacturing.[29] Application case studies, representative of various industrial sectors were performed to ascertain the actual benefits realised by DeviceNet users.[30] The case studies are based on interviews with control system engineers who discussed their experiences with fieldbus.

Eight companies were investigated, seven had installed multiple networks. One was in the process of examining the use of open networking technology, and was able to comment on perceived benefits based on proprietary networking knowledge.[31]

The companies involved were from the automotive, building materials, computer manufacture, packaging, paper production and water treatment industries. These were among the earliest implementations of DeviceNet in Europe.

4.2 Automotive

According to Josphine Robinson, DeviceNet is used by Ford for PC control of automotive transmission assembly lines.[32] Seventy industrial PCs are linked by Ethernet, each controlling a single DeviceNet network. The DeviceNet networks comprise 3-5 I/O blocks, 3-5 pneumatic valve manifolds and 2 AC motor drives.

1.1.1 Benefits

- Standardisation - modular design of lines, control program and DeviceNet device configurations.
- Decreased downtime due to the provision of diagnostics and modularity.
- "Data collection faster, easier and cheaper."[33]

- Ease of configuration.

The enhanced data collection ability of DeviceNet, modularity of components and lower system costs were acknowledged as the principal benefits.

4.3 Building materials

Compton John, thecontrol systems manager at Marley Building Materials stated that DeviceNet has been selected as a standard fieldbus network for all manufacturing sites.[34] Two separate site installations are examined. DeviceNet has been utilised to control the transfer of sand by conveyors to one of four silos after initial delivery from lorries at one location. The DeviceNet system comprises three networks using 2 PLC DeviceNet interfaces. One network comprises 4 weigh scales and 3 I/O blocks (Digital Inputs, Outputs and Analogue). The second network has a weigh scale, an ASI Gateway and an I/O block. The third has a single I/O block.

1.1.2 Benefits

- Standardisation of systems.
- Lower installation and commissioning costs (subcontracted).
- Space saving in panels.
- Commissioning reduced from 6 man days to 3 man days.

The ridge tile application comprises 3 networks with 60 drives (paint stirrers, conveyor drives), a weighing amplifier, proportional valves, proximity sensors, solenoids and an operator interface. The master PLC has 3 DeviceNet interfaces, one with 3 PLCs acting as slaves, 2 ASI gateways & I/O blocks, the remaining network has a further 3 I/O blocks and 2 AC drives.

1.1.3 Benefits

- Reliable real time communication between PLCs.
- Installation cost savings.
- Rapid testing of panels prior to delivery.

- Testing in situ (not possible previously).
- Reduction in panel size and number.
- Panel design effort minimised through standardisation.
- Commissioning reduced from one week to 2 days.

There are a number of significant benefits apparent from the use of DeviceNet in both projects. The use of DeviceNet for real-time communication was chosen as an alternative to interlocking PLCs together (using interposing relays), the control systems manager stated no other network was suitable.[35] This was due in part to the real time performance requirements and the lack of a control level network interface (ControlNet) for that particular PLC. The installation of hardwire interlocks was estimated to take 3 weeks, by using DeviceNet this was reduced to two days. The panel installations are decentralised to allow zoning of equipment for safety and operational reasons, enabling panel designs to be standardised. DeviceNet weigh amplifiers allows the measurement of negative tare weights (i.e. when a hopper is empty), which was not previously possible (using 0 - 10mv). With a calculated error of 3 kilograms on each mix, one hopper would waste £97 of material per day, £35,500 per year. The study was conducted shortly after the initial installations, the senior installation engineer later stated that ease of maintenance was also a benefit and the fieldbus technology was simple to use.

4.4 Computer assembly

DeviceNet is utilised to control operator stations on a conveyor, all the networks are similar, approximately 15m long. A typical network has 26 photoelectric sensors and 3 I/O blocks (input & output). The I/O blocks integrate proximity sensors and pneumatic solenoid valves. Brian Loy of Compaq described the main benefits listed below.[36]

1.1.4 Benefits

- Installation reduced from 2 weeks to 5 days.
- System construction and testing off site.
- Ease of Configuration and Maintenance.

- Reduction in cabling.
- Increased flexibility (through easier system reconfiguration).

The main benefits realised were the speed of installation and ease of maintenance. The diagnostic capability of the network was a prime factor in the decision to use this particular fieldbus.

4.5 Packaging

Bill Wyville of Tambrands indicated that DeviceNet is utilised to control the delivery and packaging of hygiene products, interfacing 60 small variable speed drives, 6 larger AC drives and 20 I/O blocks. Twenty-five production machines discharge to a nine lane mass conveyor, which then discharges to three lanes and subsequently to a dedicated bundling and carton line.

1.1.5 Benefits

- Control system saving - 46% (traditional compared with DeviceNet).
- Installation without production disruption.
- Flexibility.
- Standardisation - modular design enabling reuse of control program and DeviceNet device configurations.

Use of DeviceNet in this application gave significant cost and commissioning savings. Undisrupted production during installation was believed to be an important benefit. The flexibility of the network was crucial to installing additional lines without major control system changes. Incorporation of the extra lines using traditional methods would have been impossible to design and implement due to time pressures.

4.6 Paper production

DeviceNet has been installed on two reel-handling machines located at the end of the paper production process. Phil Stewksbury of Arjo Wiggins said the machines remove full reels and prepare new tubes to accept paper.[37] One network is used to control each machine, comprising a small PLC with two AC drives, 7 photoelectric sensors and 16 proximity sensors connected individually with a DeviceNet interface for standard (not networked) sensors.

1.1.6 Benefits

- Reduced wiring.
- Faster and easier commissioning - reduced by 50%.
- "Plug and play" diagnostics.
- Standardisation of design, configuration and system programming.

DeviceNet was specified mostly for diagnostic and commissioning reasons. Significant time savings were made during system design and configuration.

4.7 Water treatment

DeviceNet was being evaluated by Dewplan for the control systems of treatment plants, for potential use in power stations, refineries, chemical plants, silicon manufacture and other high technology industries. DeviceNet was considered for process monitoring and the internal cabling of Motor Control Cubicles (MCCs). Following a detailed discussion with the Controls and Instrumentation manager, Mr Andrews, the main benefits anticipated from DeviceNet implementation are given.[38]

1.1.7 Benefits

- Commissioning: Hardwired 7 -10 weeks reduced to 7 - 10 days.
- Design effort reduced by almost 50% (man weeks).
- Ability to connect a laptop computer to configure and check system.
- Flexibility in design (in comparison with a proprietary network).
- Standardisation (reducing design and commissioning further) - changes easier to incorporate.
- Reduction of inter-panel wiring (reduction in panel complexity and design effort)
- Panel space saving or do without panels entirely.

- Cabling off site possible.

The preciseness of the expected benefits is due to the experience gained in the implementation of proprietary networks, network planning (including installed cost analysis) and discussion.

4.8 Application

A comprehensive insight into the impact of fieldbus technology was achieved during the preparation of these case studies. Discussions involving project engineers presented information that was previously intangible and not available from companies or fieldbus organisations. Evidence of actual benefits in different industrial sectors has been obtained.

The knowledge acquired during the case studies has been disseminated to system integrators and end users through discussions in companies, visits to the University, trade shows, conferences, presentations and Rockwell Automation marketing material. Examples of the savings achieved are included in the draft fieldbus guide soon to be published by the British Standards Institution. The use of real application benefits in place of anticipated gains has been influential in the decisions taken by fieldbus implementers.[39]

5 Fieldbus demonstrator case study

5.1 Overview

The adoption of the open fieldbus systems relies on the fieldbus technology operating reliably when composed of multi-vendor equipment. If devices fail to communicate the user will have difficulties determining the cause and the offending equipment. Therefore the interoperability of equipment from multiple suppliers needs to be shown. In order to illustrate interoperability and the benefits of fieldbus technology, a fieldbus demonstrator has been developed. Hardwired I/O has been completely replaced by a DeviceNet network and devices, exceeding 50 nodes, with equipment from over 30 different manufacturers (Figure 9).

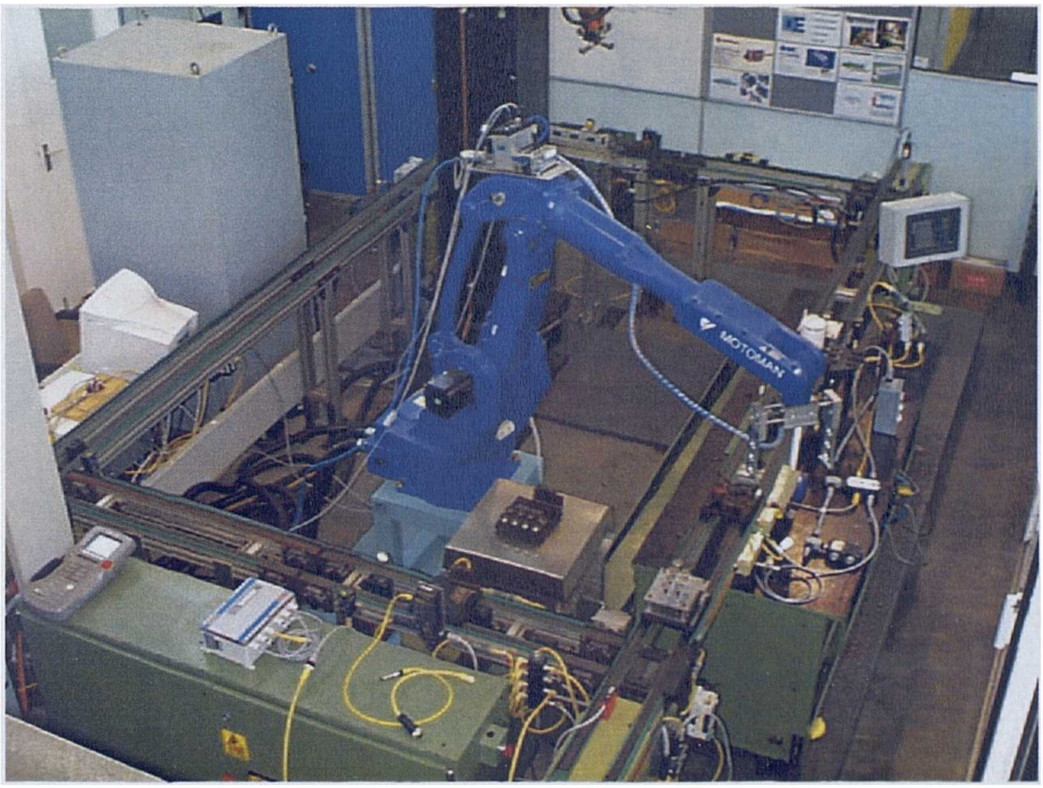


Figure 9 Fieldbus demonstrator

The demonstrator is a fixed display located in the engineering hall of the International Manufacturing Centre, Warwick Manufacturing Group at the University of Warwick. The flexible assembly cell consists of a rectangle of conveyor (2.5m x 4.5m) for moving pallets, with two robots performing assembly and weighing operations. DeviceNet provides diagnostic information that would not be available using the old traditional parallel wiring method or legacy networks. To demonstrate this facility a large LED (light emitting diode) message screen and a Supervisory Control And Data Acquisition (SCADA) software package have been installed. Both are interfaced to the PLC controlling the cell. DeviceNet equipment is installed to show variety and particular network features.

5.2 System architecture

The principal demonstrator networked components are shown in Figure 10.

The PC has four functions:

1. Online and offline programming of the PLC.
2. DeviceNet scanner and device configuration (device configuration is also performed with a hand held configuration tool or a laptop PC with PCMCIA DeviceNet interface).
3. SCADA configuration and display.
4. Internet web server (for SCADA information).

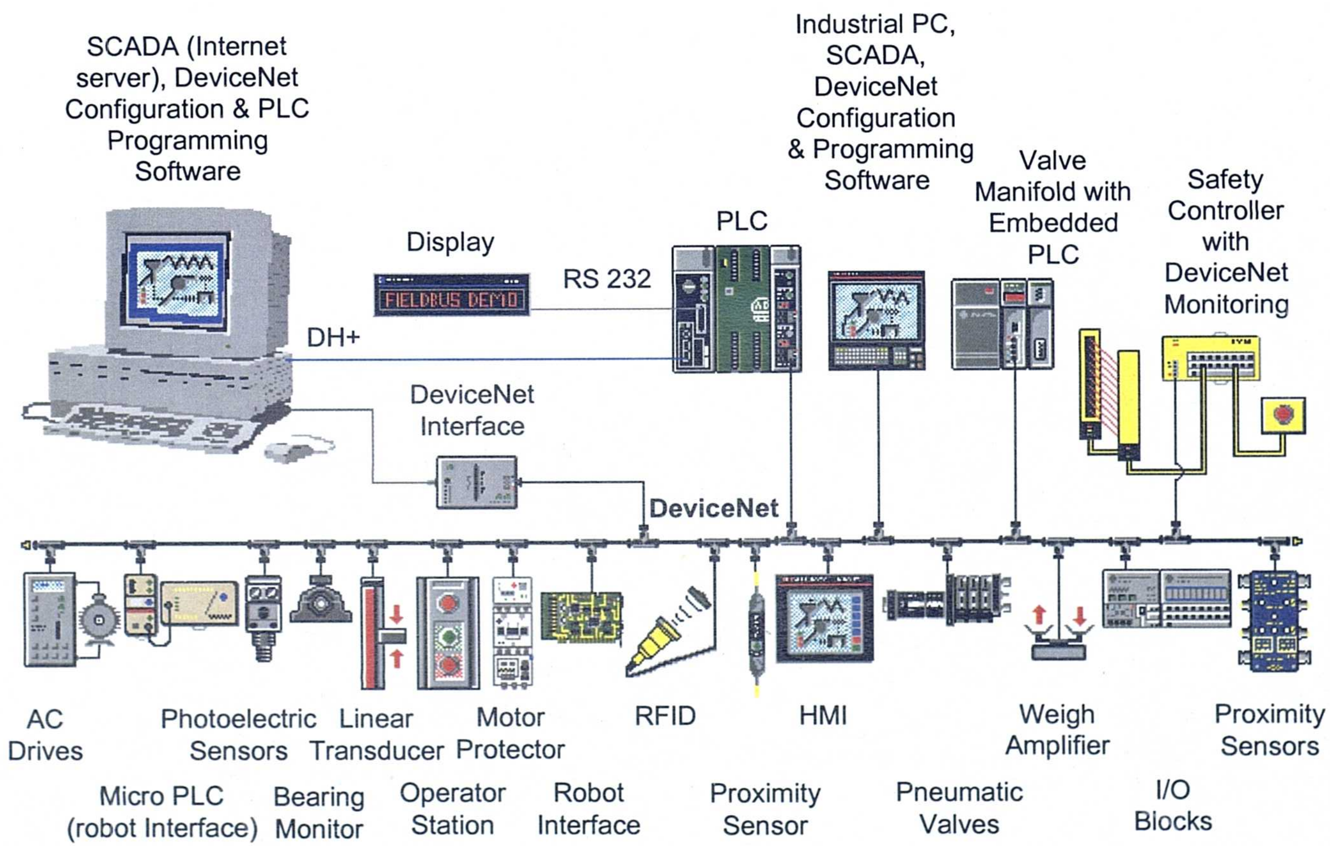


Figure 10 Demonstrator architecture[40]

The Industrial Personal Computer (IPC) is used for real time control, demonstrating an alternative control strategy to the more traditional use of a PLC.[41]

The IPC has the following functionality:

1. Online and offline programming.
2. DeviceNet interface and device configuration.
3. SCADA configuration and display.
4. Internet web server.
5. HMI configuration.

Many functions of the PC and PLC can be combined on one platform on an IPC, in some circumstances, providing a cost-effective alternative.[42]

5.3 System Integration

The PLC controls the conveyor devices via the DeviceNet scanner module, transferring device input/output and scanner/network status information. The PLC program incorporates a routine developed to display device and network errors. When errors are induced, for demonstration purposes by removing multiple devices, network communication errors are indicated with device specific fault and location information. The messaging display is driven by the PLC via RS -232 communication (installed prior to the availability of suitable DeviceNet displays). SCADA and the PLC programming software utilise Data Highway +, an Allen-Bradley (a Rockwell Automation brand name) proprietary network interface available on the PLC processor. This avoided the addition of further network interfaces in the PLC rack. It is regarded as important to show one network interface can replace all the original PLC I/O cards.

An embedded PLC has been incorporated into the system to show the potential to remove the control cabinet required by a PLC, by placing the embedded device directly on the machinery. Control cabinets are custom built at a significant cost, and due to their size can restrict the view of operations.[43] Ford Halewood have attempted to minimise the visual obstruction that control cabinets can cause in a DeviceNet installation, as part of their visual factory principle.[44] The addition of another PLC proves the multi-master capability of the network (some networks only allow one controller). The embedded PLC is mounted on the Motoman robot, operating the robot gripper and providing feedback.

The ASEA robot has been interfaced via a micro PLC by an MSc student.[45] Hardwiring of the I/O between the robot and the PLC has been kept to a minimum by placing the micro PLC adjacent to the robot controller. The micro PLC program has also enabled the number of wires to be minimised and reduced the data transmission to the PLC. This is achieved by providing local control and status feedback, rather than simply I/O messaging. The ability of the network to support decentralised control is therefore demonstrated.

The radio frequency identification system (RFID) has been replaced as part of the same student project, to indicate the broad spectrum of equipment that can be used on DeviceNet. The RFID system enables the identification of pallet type and current status (full or empty) with data being read and written by the PLC according to robot operation (controlled by the PLC).

DeviceNet integration of the Motoman robot was less complex, being a network interface card directly mounted in the robot controller. Messaging between the PLC and robot appear as local I/O to both, removing the need for the time consuming wiring required to interface the ASEA. The difference was considerable, to interface the ASEA required the author and student to study wiring diagrams of the robot I/O, which was found to have few I/O points left. A scheme was then developed for the communication, programmed in the micro PLC, to maximise the remaining available I/O. Whereas the Motoman installation took minutes, only requiring network settings and I/O sizes to be specified. The I/O available on the interface allowed for further expansion and did not limit existing robot I/O.

Human Machine Interface (HMI) enables comprehensive operator monitoring and control of the system. Monitoring of system status, drive speed & current, motor temperature, linear &

shaft position, pallet status and device diagnostics is possible. The producer/consumer based communication of the network is fully implemented in this device and allows integration of HMI of this sophistication on to a device level network. Even though all other devices are configured to respond as slaves to the PLC master when communicating, the HMI is set to produce data at the request of the master (PLC) and consume responses (to master requests) from selected slaves. This avoids duplicate messaging to PLC and HMI from slaves, significantly reducing network bandwidth utilisation. If the same functionality were to be implemented using a source destination network, each slave device would need to respond to communication requests from both the master PLC and HMI. This is would cause a substantial increase in network traffic, likely to impact the real time quality of the network, becoming unsuitable for device control.

The SCADA and Internet server were implemented as student projects.[46] The SCADA was originally configured to show status and limited trending and diagnostic information.[47] The SCADA functionality has been enhanced to demonstrate the diagnostic capability of the network, by incorporating graphical and textual indication of device status and fault conditions. Development of the Internet server has been completed to prove the concept of remote monitoring using 'live' data.[48] While data cannot be provided in real time due to Internet access, system information has been shown to be accurate to within seconds.

5.4 Research engineer contribution

Dr. Ken Young initially implemented DeviceNet on the demonstrator, to a point where the control system was a mix of hardwired and fieldbus devices from a limited number of manufacturers. The research engineer obtained and integrated a wide range of fieldbus devices to show true multi-vendor interoperability and the benefits of fieldbus. The ASEA robot, two Personal Computer controllers, Internet monitoring, Promise (DeviceNet network design software update of the original work completed by the research engineer) and partial Supervisory Control and Data Acquisition (SCADA) package integration were student projects supervised by the research engineer.

5.5 Further work

New features of DeviceNet incorporated into new products will be integrated. This will include a facility to automatically reconfigure a device should a replacement be connected to the network with the identical characteristics. A paper based on a portfolio submission is planned to highlight the advantages of peer to peer communication, and how it has been applied on the demonstrator.[49]

The combined use of Unified Markup Language (UML) and Extensible Markup Language (XML) will be investigated. On going work is already utilising UML in the SALVO control system for object orientated programming. XML offers a neutral language for UML data transfer, device profile definition and possibly function blocks.

5.6 Innovation & application

The fieldbus demonstrator at Warwick is a unique facility showing a range of working, interoperable equipment from a large number of different manufacturers. The interoperability of devices is crucial to the success of open fieldbus technology, this facility clearly demonstrates equipment interoperability.

The integration of prototype devices has given companies the opportunity to test devices in an interoperable environment not normally available to them. Where devices have not functioned properly, or have not been implemented correctly according to the DeviceNet Specifications, the circumstances have been reported to the companies concerned. This has assisted companies in the development of product and afforded significant cost savings. Fieldbus users have also been spared the inconvenience of system failures, avoiding performance and suitability fears of the new technology.

The fieldbus demonstrator has been used to illustrate the advantages of fieldbus technology to potential users. The facility shows how system complexity can be reduced with less cabling, while system functionality is enhanced. The capability of fieldbus to improve diagnostics and to support alternative control methodologies (utilising HMI, multi-master &

highly distributed control) is shown. The flexibility and ability to rapidly reconfigure the network and devices is also demonstrated. The demonstrator displays the key benefits that manufacturers can achieve to meet business demands. For example, the Ford plant manager, Miro Suga indicated that the long-term objectives of having a re-usable and convertible plant have been achieved at Halewood. Fieldbus technology has enabled the fast installation and launch of new assembly lines, increasing reliability, maintainability and flexibility.[50]

These benefits have been disseminated to a wide audience. Most companies (OEMs, system integrators and end users) that have implemented or are evaluating DeviceNet have visited the demonstrator, including AWRE, BMW, BNFL, Cadbury, Compaq, Ford, GlaxoWellcome, Gillette, Honda, Jacobs Suchard, Marley Building Materials, Nestle, Rover, Seven Trent Water and Thames Water.[51] The demonstrator has been featured in a number of national and international conference presentations and papers.[19,52,53,54,55]

6 Transitory connections utilising fieldbus

6.1 Fieldbus benefits

The benefits most frequently cited by users of fieldbus technology have been flexibility, design, speed of commissioning, diagnostics and maintenance. The exchange of digital information is also considered important, providing more accurate data capture than analogue systems and allowing the use of data that was previously unavailable.[56] These benefits can be utilised in new areas with the novel application of fieldbus technology.

Work done at the University of Warwick by the author has shown fieldbus can be used over transitory connections for robotic tool changers and laser scanners used for machine safety. Transitory connections in this instance are those network connections that are designed to be disconnected and reconnected whilst the network is under power.

Dr. Young had demonstrated the use of fieldbus with transitory connections to pallet tooling on the SALVO project. Further development by the author in collaboration with Sick & Pilz has incorporated connectivity for a machine safety network on the same tool pallet. The research engineer has achieved similar benefits with fieldbus transitory connections implemented on a robotic tool changer.

Use of a safety-related fieldbus has enabled the provision of safety measures in an application, which would not otherwise be feasible using traditional hardwiring, due to the complexity and large amount of wiring required.

The reduction in the number of cores has been achieved by the use of fieldbus in new applications, such as over slip rings, flexible and transitory connections, where the large number of conductors/connectors required would previously have been prohibitive.

6.2 Controller Area Network over slip rings

The Controller Area Network (CAN) technology has been used successfully in proprietary and open protocol formats over slip rings to simplify systems engineering. A proprietary CAN application example involves the indexing of a registered embossing machine for beer can manufacture. CAN data, regulated and unregulated 24v and 3-phase power are all passed over slip rings to 24 servo drives. The application design was based on CAN from the outset by the system integrator, simplifying complicated system integration.[57] DeviceNet has also been utilised over slip rings to control the manufacture of car seat foam for similar reasons. A networked programmable logic controller (PLC) controls the moulding process on a continuous track with drives and via slip rings, pneumatics and thermocouples.[58] Both applications have proved very reliable according to the system integrators, with no faults experienced due to the transmission of data in this manner.

6.3 Robot flexible couplings and links

Development of a prototype smart petrol pump, capable of opening a filler cap, inserting a hose and filling a fuel tank, suffered significant electrical noise problems, mainly due to the large volume of hardwiring. DeviceNet is used to replace the hardwiring (with I/O points along the length of the robot arm), reducing sensor wiring, enabling fuel, hoses, motor wiring, and pneumatics to be routed through three gantry racks and two rotational links. The system integrator said the use of fieldbus in this application was essential in the development of the final prototype, enabling the sensor wiring to be kept to a minimum.[59]

6.4 Transitory connections using CAN

Three applications have utilised the need for fewer wires, and the ability to add and remove devices from a fieldbus under power. All the applications are in the SALVO (Structurally Advanced Light Weight Vehicle Objective) cell, two DeviceNet transitory connections are used on separate networks, one on a conveyor, the other on a robot (Figure 11). The third network is Safetybus p, (another CAN based fieldbus) used purely for connection of safety devices (emergency stops, light curtains laser scanners & safety relays). The conveyor transitory connection is used to connect networked devices on a tool (DeviceNet & Safetybus

p) as it travels along the conveyor and is reconnected at each robot station. The robot transitory connection is for a tool changer.

6.5 Tool pallet quick connect

A complex body in white assembly tool moves between three cells (Figure 11). The tool pallet has twelve automatically controlled clamps each driven by a locking cylinder, with a minimum of two sensors per cylinder to hold the work piece and two laser scanners provide safety guarding. The tool is located on a pallet that runs along a roller conveyer 18m long. When the tooling enters a cell it is first located on the conveyor by a shot bolt and then a quick connect device with DeviceNet, Safetybus p, 24v power and a pneumatic supply hose is fired into a docking plate on the tool. Once connected the four nodes that control the tooling (three solenoid banks and an I/O block) and the laser scanners secure communication with the PLC and safety controller respectively, then the tooling actions commence.

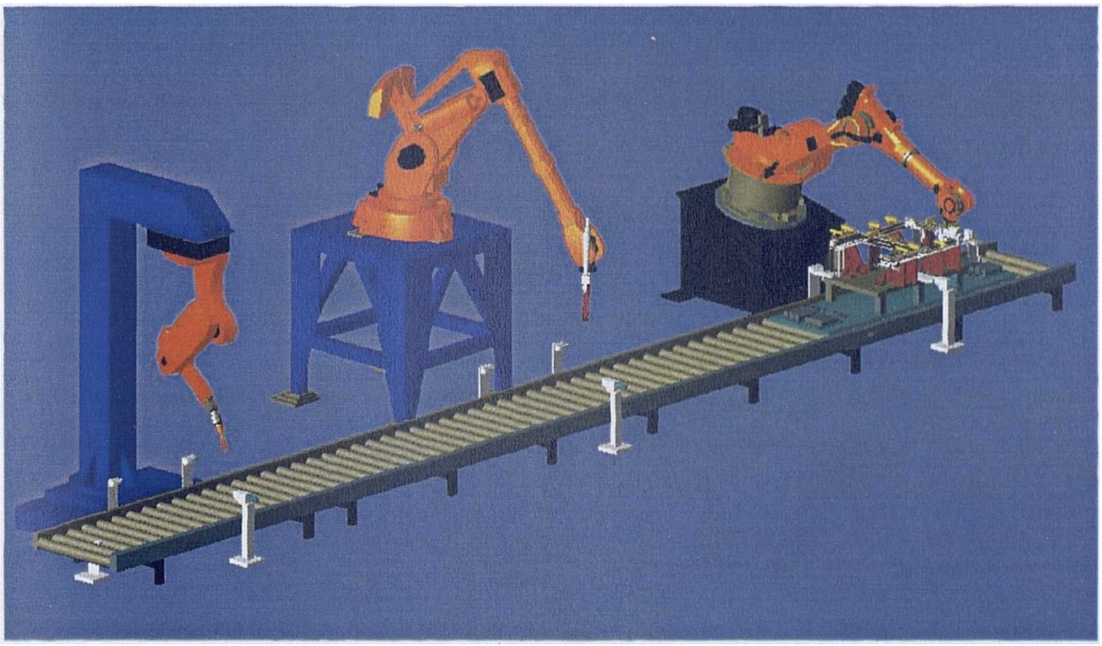


Figure 11 SALVO cell showing the tooling, conveyor and robots

Had traditional wiring been used, the number of individual connections would be far greater, complicating fault finding and repair. With just five connections the size of the pins can be larger, increasing robustness and duplicated to give redundancy if required. This has not been done on this occasion. No failures due to the quick connectors have been logged by the SCADA package in over 20 months of operation.

6.6 Robot tool changer

The tool changer is mounted on the central robot of the SALVO cell (Figure 11), on the wrist of an ABB robot. The DeviceNet network runs from a PLC, into the base of the robot, exits half way down the arm and is connected to the fixed half of the tool changer (Figure 12). The trunk (thick) cable is terminated in the connector of the tool changer, with the drop (thin) cable passing through the tool changer contacts via a termination block and to a DeviceNet I/O block.

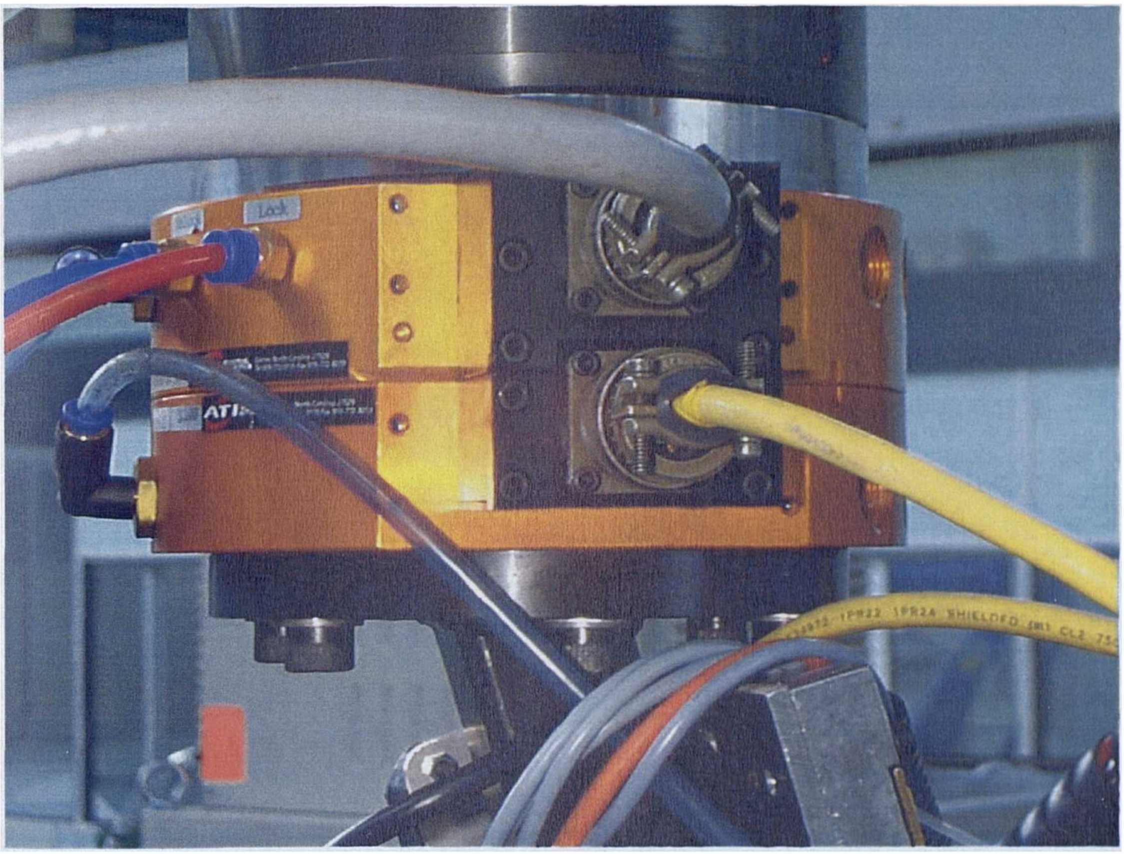


Figure 12 Tool changer showing DeviceNet trunk and drop cabling

The network utilises the standard connections provided at the robot base and on the arm. Five pins (2 power, 2 signal and shield) have been used on all network connections except the tool changer contacts. These were duplicated for redundancy when intermittent network errors were discovered, believed to be due to the size of pins. By using the network the PLC is able to detect tool connection and identify tool type. This is achieved by assigning a unique (network) identity to each I/O block mounted on a tool.

The tool changer provides transitory connections for the network and pneumatics to control a self-drill drive screw. The single I/O block is sufficient to provide all the required inputs and outputs.

Similar benefits have been achieved with the tool changer as with the conveyor quick connect. The reduction in wiring complexity would facilitate rapid fault diagnosis and repair, had there been any problems. The reduction in cabling down the arm has made cable dressing easier and more robust. Tool identification is set via software (over the network) by changing the network address of the I/O device, providing a more secure and less error prone method than manual coding.

6.7 Innovation & application

The novel use of fieldbus for transitory connections is a new application of the technology. Transitory connections are not possible for all fieldbus technology, for example a ring topology network that reconfigures node addressing on device disconnection. The use of transitory connections with CAN based networks has proved the viability of the concept, affording greater flexibility and functionality. The utilisation of a safety network (in place of hardwiring) is not yet accepted practice by the Health and Safety Executive (HSE).[60] The use of transitory connections for safety inputs is a demanding test of the technology, and is not possible with traditional methods.

Fieldbus work performed (tool changer & Safetybus p) in the SALVO project has been disseminated to participating companies through presentations, visits and journal papers.[61,62] The safety fieldbus component has been used to demonstrate the technology to HM Factory Inspectors (HSE) in order to promote its acceptance. The safety-related technology was also displayed at the UK launch, held at the University.

7 Safety related fieldbus

7.1 Introduction

Traditionally machine safety systems (used for the avoidance of personal injury) have been hardwired, with standards and legislation restricting the use of programmable controllers and networks. Hardwiring tends to make safety systems complex and difficult to maintain. Emerging safety-relevant fieldbus will change this, eventually offering similar benefits to existing fieldbus technology:

- Increased safety function security (tamper protection).
- Improved diagnostics.
- Reduced complexity.
- Reduced downtime.
- Rapid troubleshooting.
- Greater ease of maintenance.
- Reduced wiring and installation cost.
- Reduced commissioning time.
- Configuration of devices over the network.
- Devices from multiple vendors.

Safety relevant fieldbus systems need additional features to ensure fail safe action and reliability in order to meet present and emerging safety standards and legislation. These requirements are not yet formally standardised, but work is being done by approval bodies and others.[63] A situation has arisen where existing legislation or standards have not kept pace with technology. This has caused manufacturers, certification bodies and Government agencies to seek and justify best practice in the face of incongruent and inapplicable standards legislation.

The application of a safety-related fieldbus replacing a traditionally hardwired system, has been completed in order to evaluate and demonstrate the technology. The acceptance of fieldbus and logic controllers in safety-related applications is necessitating a fundamental shift in machine safety principles, which is not yet complete. Work has been done to promote the application of safety-related fieldbus and to investigate and implement the necessary safety features in an existing fieldbus technology.

7.2 Safety fieldbus benefits

Improved safety security can be achieved by the reduction in the wiring necessary for the safety system and pass wording of configuration parameters and control programmes. These then make unauthorised adjustments to control systems less likely, maintaining system safety integrity, which may have been lost had such adjustments been attempted.

Traditional hardwired safety systems can be complex with little in the way of operational status or diagnostics of devices available system wide. This makes the identification of the causes of safe shutdown more difficult to detect, e.g. emergency push button, light curtain or device failure. The use of intelligent fieldbus enables safe shutdown causes to be rapidly identified (whether due to unsafe conditions or system faults) and rectified, an important factor when the cost of down time is considered (e.g. £15,000 per minute at Ford Dagenham).

Diagnostics on the installation at Warwick, identifies critical safety conditions such as system faults, e.g. relay or emergency stop switch failure (conditions preventing machinery operation) or operational status, e.g. door interlocks active or an emergency stop activated. Previously, hardwired (relay) safety circuit monitoring by the PLC was 'go/no go', with no indication as to what may have initiated a safe condition, and no diagnostic capability. Often, this meant checking each emergency stop in the SALVO cell, now they can be individually identified.

The reduction in complexity will lead to faster installation and commissioning, particularly where the diagnostic capabilities are utilised. These factors in turn facilitate greater ease of maintenance, reduced down time and reduced lifetime ownership costs.

The ability to configure devices over the network offers distinct advantages. All devices can be configured from one point, rather than having to connect to individual devices. In the case of more complex devices such as laser scanners (zone configuration) and light curtains (blanking and masking), the ability to up load and down load pre-configured files to multiple devices could save valuable commissioning time and reduce down time.

7.3 Safety

Safety is defined as the freedom from unacceptable risk.[64] Control systems may be either operationally safe or fail safe.

- Operationally safe requires ultra high reliability and a minimum safe (redundant) operation. There is no fail-safe condition for the system, for example a flight control system.
- Fail safe demands a high level of error detection. The safe state is identified and reached when a failure occurs and the control system/machine is then switched off.

7.4 Reliability

Reliability is defined as the probability that an item can perform a required function under given conditions for a given time interval.[65] IEC 61508, Functional safety of electrical/electronic/programmable electronic safety-related systems standard, takes this concept a stage further and describes safety integrity levels (SIL). Safety integrity is defined as the probability of a safety-related system satisfactorily performing the required safety functions under all the stated conditions, within a stated period of time.[66]

7.5 Legislation & standards

Safety of machinery in an industrial environment is governed by many standards, some being very recently introduced, others are still under preparation. Existing standards do not necessarily reflect the present state of the art, the most obvious being EN 60204. Other standards such as IEC 61508 have been introduced to fill this gap, and facilitate the production of 'daughter' standards for specific sectors. Table 3 shows the principal standards and legislation affecting safety fieldbus implementation in the industrial sector.

Standard	Relevance
EN 60204 Electrical Equipment of Industrial Machines	• Emergency stop (cat.0) "shall not depend on electronic logic (hardware or software) or on transmission of commands over communications link or networks" • Emergency stop (cat.1) "final removal of power to machine actuators shall be ensured and shall be by means of electromechanical components"
IEC 61158 Fieldbus standard for use in industrial control systems	Under development for over fourteen years, with Part 2 approved.[67] • The addition of fault tolerance for safety related applications is a likely new work item.[68]
IEC 61508 Functional safety of electrical/ electronic/ programmable electronic systems	• Generic standard covering the safety lifecycle of all E/E/PESs, to facilitate development of application sector standards. • Risk assessment – for safety functions & safety integrity levels (SIL). Part 2 of this standard will include risk assessment for data communications.
EN 954 -1 Safety Related Control Systems	Describes the categories, requirements, functional characteristics and principles for the design of safety (fail safe) related control systems. • Category 1. - 'well tried' principles, logic/software has not previously been considered adequate. • Category 4. - any single fault must be detected at or before the next call on the safety system or an accumulation of three faults shall not lead to loss of the safety function.
EN 50159 Railway Applications - Part 2. Safety related communication in open transmission systems.	Standard specifies the safety requirements for data communications in a safety-related electronic system. Currently the only European standard that deals with data communication in safety-related applications. A guide to defences is given to defeat the various threats identified.[69]

Table 3 Principal standards affecting safety-related fieldbus

Berufsgenossenschaftliches Institut fur Abeitssicherheit (BIA), the German certification body is currently working with manufacturers to produce a specific standard for industrial safety fieldbus based upon EN 50159. The BIA approach is to take a non-safety related fieldbus, which is considered as inherently unsafe and recommend safety procedures that ensure fail safe operation (Table 3).[70]

	Measure						
Transmission error	Running Number	Time Stamp	Time Echo	Echo	ID for Sender and Receiver	Data CRC	Redundancy plus Cross Check
Double Received Message	YES	YES	-	-	-	-	YES
Loss of Message	YES	-	-	YES	-	-	YES
Message Insert	YES	-	-	YES	-	-	YES
Sequence Failure	YES	YES	-	-	-	-	YES
Data Corruption	-	-	-	YES	YES	YES	YES
Delay	-	YES	YES	-	-	-	-

Note: At least one error correction/detection mechanism must be implemented per type of failure.

Table 4 Error prevention mechanisms recommended by BIA

The BIA has also considered different bus architectures for reliability:

1. Standard serial bus (single channel).
2. Redundant bus, no common parts.
3. Non-redundant bus, separate transceivers and processors.
4. Non-redundant bus, common transceivers and separate processors.

The standard bus achieved SIL 1, all others achieved SIL 3, which is satisfactory to meet the EC Machinery Directive (SIL 4 being the highest).[71] The applicable Safety Integrity Levels for a fieldbus are described in IEC 61508-1 (General requirements) and shown in Table 5. High demand or continuous mode of operation SIL is used since no immediate intervention, other than redundant operation, can take place when dangerous failure occurs. The standard sets a lower limit on the target measures in a dangerous mode of failure (otherwise referred to as the frequency of dangerous failure or dangerous failure rate) that may be claimed by a manufacturer.

Safety Integrity Level	High demand or continuous mode of operation (probability of a dangerous failure per hour)
4	$\geq 10^{-9}$ to $< 10^{-8}$
3	$\geq 10^{-8}$ to $< 10^{-7}$
2	$\geq 10^{-7}$ to $< 10^{-6}$
1	$\geq 10^{-6}$ to $< 10^{-5}$

Table 5 Safety Integrity Levels for safety-related E/E/PE system operating in high demand or continuous mode[72]

7.6 DeviceNet safety fieldbus

The feasibility of DeviceNet, a standard (non-safety related) fieldbus for safety related functionality has been investigated. With reference to standards (current & proposed) and BIA recommendations, the additional features needed to meet the requirements of machine safety for DeviceNet have been developed.

The proposal is the basis of the functional specification for a safety-related implementation of DeviceNet by Rockwell. It is envisaged the specification will achieve IEC 61508 SIL 3 and EN 954-1 Category 4. This information is company confidential.[73]

7.7 Safety fieldbus implementation

The author has installed Safetybus p, a Pilz safety fieldbus, (with hardware and software assistance from Pilz and Sick) in two robotic cells at the University of Warwick. This is the first application to demonstrate a complete fieldbus control system architecture. Figure 6 shows the actual architecture of the SALVO cell, utilising Ethernet, ControlNet, DeviceNet and Safetybus p networks. The safety fieldbus technology integrates emergency stop buttons, light curtains, laser scanners, safety interlocks and robot safety circuits to a safety controller. The technology is approved for machine safety to up to Category 4 (EN 954-1 1994 Safety related parts of control systems – general principles for design) by the BIA.

The safety fieldbus installation provides machine safety in two physically separate robot cells, the Structurally Advanced Light Weight Vehicle Objective (SALVO) and the Flexible Tooling System (FTS). The SALVO application comprises 3 robot cells, with a conveyor linking the cells. The FTS cell has 3 co-operative robots, used to investigate the use of flexible tooling in the assembly of aircraft wing structures.

The Safetybus p installation comprises one programmable safety controller acting as a network master, 4 digital input/output adapters, 4 laser scanners and 2 light curtains. The network architecture is shown in Figure 13.

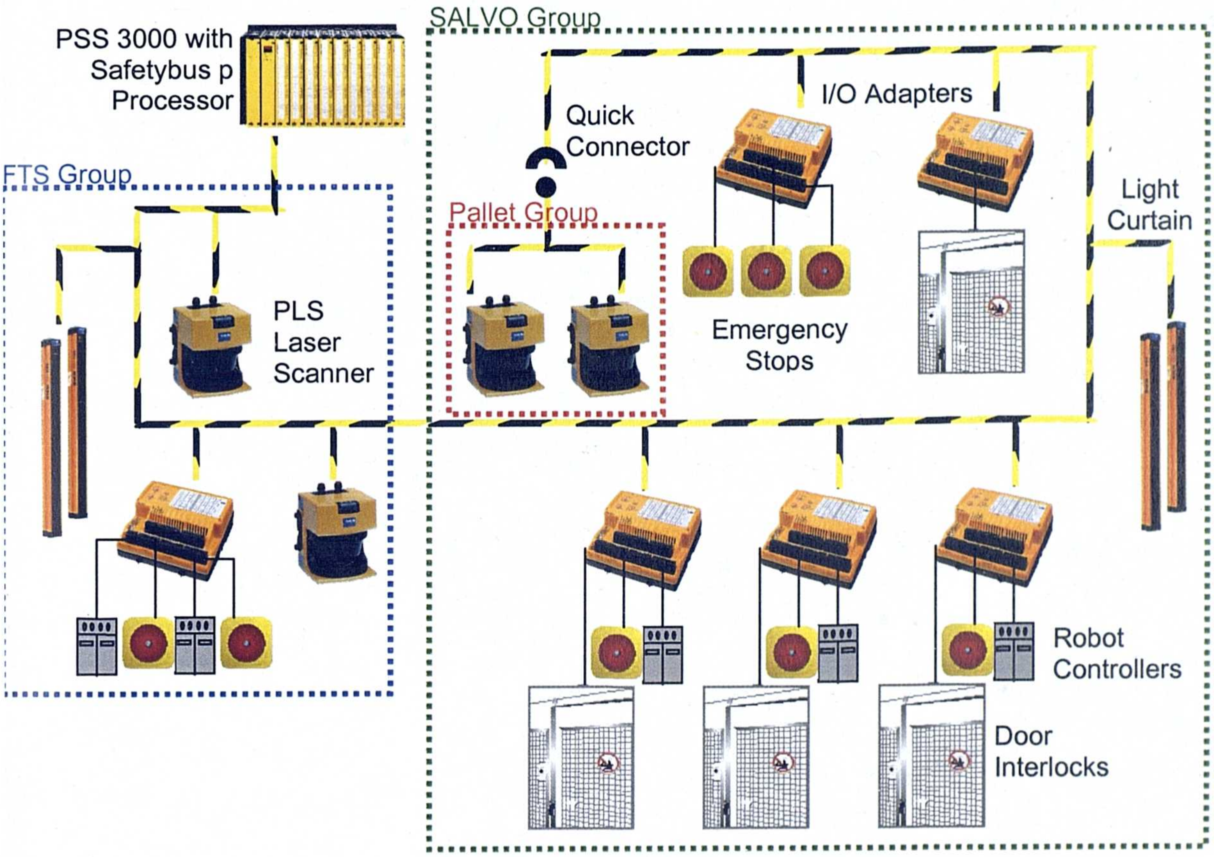


Figure 13 Safetybus p installation architecture

Safetybus p allows control of groups of devices in the case of a safety input or bus/device failure. This enables the FTS and SALVO cells to operate independently, even though both are on the same network and safety controller. The ability to stop and restart groups of devices on the network is used with the laser scanners (and adapters for node recovery).

Prior to disconnection of the pallet, the PLC sets an input (via DeviceNet/ControlNet) in the standard I/O section of the safety controller, indicating pallet motion. This input initiates the laser group to be set to stop in the failsafe section of the controller, allowing the devices to be disconnected without putting the SALVO cell into a safe condition. Upon reconnection, communication is established and the laser group is set to restart, it is then operational again.

7.8 Further work

Rockwell Automation has requested further assistance in the development of the functional specification of a safety-related DeviceNet. The implementation requires development of a complete system specification, including a controller, safety I/O and various interfaces depending on the networking strategy.

The Safetybus p installation at Warwick is new, and will require further evaluation. This is due to the fundamental changes it will bring to the safety system applications. Dissemination of the experiences and benefits of the technology will take place through the publication of papers (including the portfolio submission), collaboration with the HSE and visits by potential users.

7.9 Innovation and application

The use of a fieldbus purely for safety devices is new, this is the first evaluation of the technology in an integrated application. The use of quick connectors within the machine safety environment is unique. The application has been used to demonstrate the viability and functionality of safety fieldbus technology to the Health and Safety Executive.

As mentioned previously, the use of fieldbus in safety-related machine applications is new and is currently under development in a number of organisations. The research engineer presented the market position (potential manufacturers and users) to Rockwell Automation in order that development of a DeviceNet solution was begun. The author investigated best practice in the transmission of safe data over networks and related machine safety legislation, then determined the requirements for safety-related fieldbus.

Identification of the necessary safety measures and subsequent proposal to implement them in DeviceNet is new, and represents a novel application of an existing fieldbus technology. The proposal will form the foundation of a safety-related functional specification being developed by Rockwell.

Safety-related fieldbus presentations have been made to the CAN in Automation (CiA) safety related study group (at their invitation), at a leading automation conference, and at University research dissemination event (Rover), in order to raise awareness of the impact the safety fieldbus will have.[74] The collaborating companies have utilised the installation for technology demonstrations to customers (including the AWE) and the HSE.

8 Fieldbus standards and committee work

8.1 Overview

Fieldbus standardisation activity has been reviewed in order to understand their development and impact on industry. Manufacturer involvement in the standards process has been an important strategy to maintain competitive position, avoiding competitor dominance of the market through technology. European legislation has affected the application of fieldbus technology, and has been used in a deliberately misleading manner by some fieldbus organisations.

Membership of the British Standards Institution (BSI) Advanced Manufacturing Technology (AMT/7) Committee (monitoring and control aspects of AMT), responsible for fieldbus standards development, was necessary to gain a complete understanding of the standards arena and their operation in the fieldbus market. Development of a guide to the evaluation of fieldbus was a significant activity during this period of BSI Committee membership.

8.2 Fieldbus standards

In 1985 the International Electrotechnical Commission (IEC) started work on defining a fieldbus standard for field instrumentation. Fourteen years later the standard has not yet successfully passed voting on all parts. Recent developments after the last round of voting have allowed the submission of additional technologies for potential inclusion in the standard, to ensure completion. The considerable delay has been due to the parallel emergence and rapid market adoption of other competing and incompatible fieldbus technologies (Figure 13). Whilst agreement was made to implement the best features of those fieldbus into the IEC fieldbus standard, the European Committee for Electrotechnical Standardisation (CENELEC, the European counterpart of IEC) started to consider a European standard to quickly meet the needs of the European market. Proposals from the French and Germans was to originally include the national standards Profibus and FIP (a forerunner of WorldFIP), however in 1997 EN 50170 was accepted with P-Net, the Danish national standard, after rejection in the first round of voting.

Confusion amongst those wishing to choose a fieldbus can be easily understood when faced with a bewildering number of different technologies and standards. Figure 14 shows the fieldbus technologies and the formation of corresponding fieldbus standards (having significant European impact) over time, with approximate dates of approval.

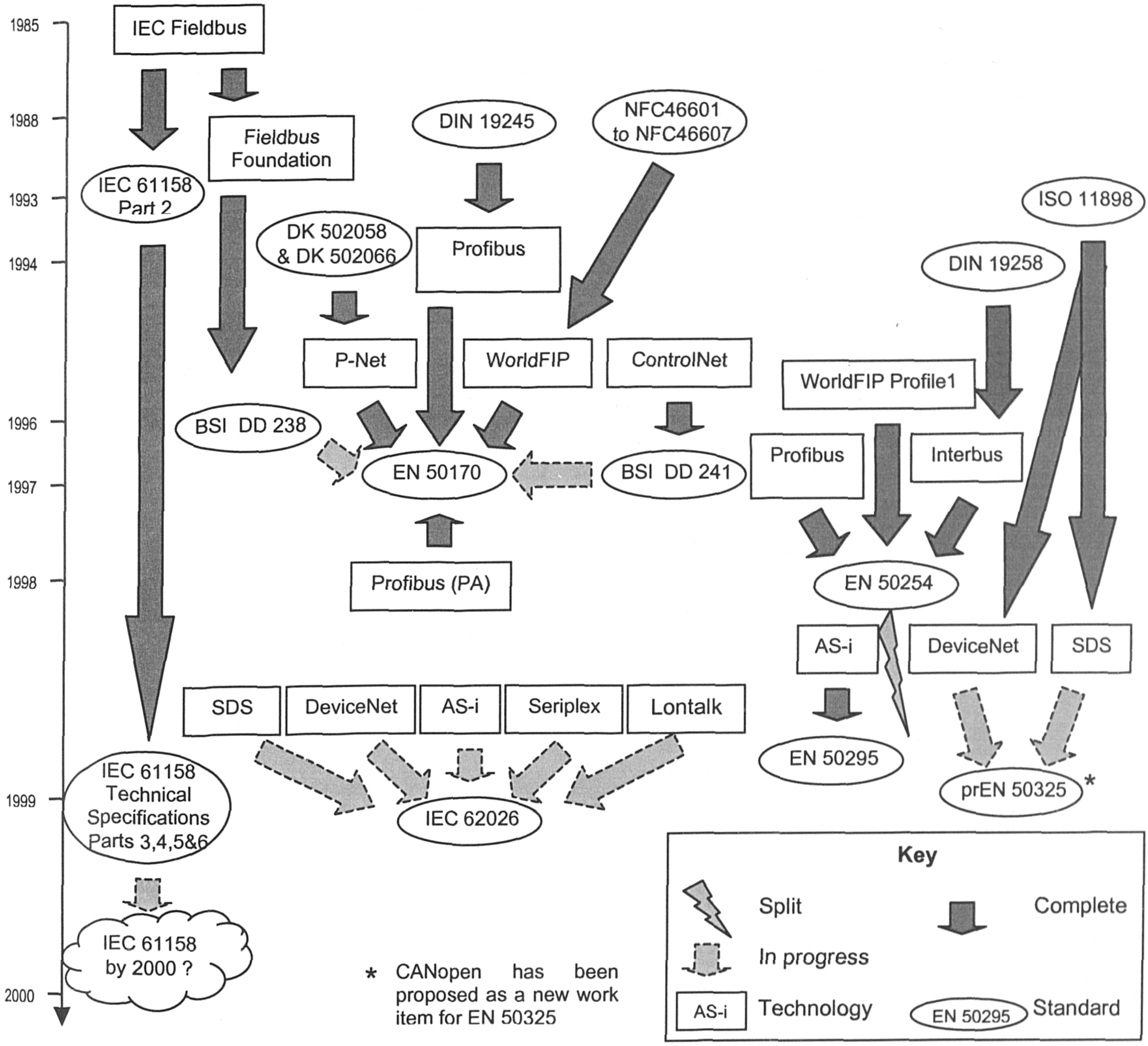


Figure 14 Standards development[75]

Figure 14 is taken from the portfolio submission The Current Fieldbus Standards Situation – A European View, written by the author and published to clarify the present fieldbus standards situation, showing standards development and current activities.[76]

The adoption of EN 50170 has made the standard legally enforceable in public supply contracts under certain conditions. This made fieldbus users wary and competing manufacturers have viewed the standard as a restriction of trade – which runs contrary to the stated aims of the EU, to promote trade and prevent protectionism. Some fieldbus organisations have misled potential fieldbus users as to the circumstances under which the standard becomes enforceable.[77] This occurs where a utility (or public authority) wishes to use technical specifications in a contract. European standards take precedence, but need not be followed if there is innovation making the use of standards inappropriate, or the standards do not take account of technical developments (since their adoption), or that use of the standard would lead to disproportionate cost/difficulty and/or equipment incompatibility.[78] This led to users of other fieldbus technologies supporting efforts to gain European standardisation as well, in order to restore a fair competitive environment. Work on low voltage switch gear & control gear standards has also sought to incorporate associated data exchange capabilities. The combination of these developments has contributed to a confusing situation.

Despite all the previous disagreements, there remains a possiblity that IEC 61158 may be adopted as a global fieldbus standard by the end of 1999, even if the eventual content is still debatable. CENELEC has also stated an intention to strive towards an international fieldbus, by adopting IEC 61158 as a EN once the technology is complete and proven.[79] However, the emergence of a number of de facto fieldbus standards has demonstrated that a single fieldbus is not suitable for all applications, and the indications are that some technologies will continue to be used.

8.3 British Standards Institution work

The BSI represents UK interests at the International Organisation for Standardisation (ISO), International Electrotechnical Commission (IEC), and in Europe at European Committee for Standardisation (CEN) and the European Committee for Electrotechnical Standardisation (CENELEC). This is achieved by project managing the production of standards and co-ordinating standards committees. The standards committees comprise anyone who has an interest, including consumers, government departments, manufacturers, research organisations and users.[77]

The AMT/7 Committee scope for the current year (1999) is to "support and co-ordinate the availability of appropriate industrial real-time communications standards (Fieldbus) to meet the needs of UK industry." To be achieved through the "leadership and participation" in the work of the various International and European standards committees (in IEC, ISO, CEN, CENELEC) which claim responsibility in Fieldbus areas.[80] This has involved the participation of the AMT/7 Committee in the development of European and International Fieldbus Standards (Figure 14), through liaison with other National, European and International Committees.

Substantial committee time has been devoted to the development of a guide to fieldbus specifications to meet the requirements of UK industry (this has also been proposed for international sale). Written contributions by the author have been accepted by the BSI committee for inclusion in the glossary, interoperability, end user savings (quoted examples) and the technical characteristics of networks (Ethernet, SDS & DeviceNet) sections of the fieldbus guide.[81] Oral contributions were made at committee meetings concerning the document, including structure, technical content and presentation.

8.4 Fieldbus standards

There are still a number of standards nearing completion, particularly 61158, which has been underdevelopment for over fourteen years. Statements by the IEC Committee of Action indicate that this standard may be completed in 2000. Manufacturers are likely to attempt to standardise safety-related fieldbus technologies. Users would be better served by manufacturers agreeing on the measures to be applied in order to achieve safe operation. In contrast to a piecemeal approach, which may ultimately standardise incompatible technologies. Continued membership of the BSI AMT/7 Committee would ensure these issues are discussed.

8.5 Application

Fieldbus standards information has been disseminated to system integrators, OEMs and end users through presentations at conferences and publications (journal and conference proceedings) in order to inform potential fieldbus implementers of their implications.[2,77] In particular, the avoidance of misinformed decisions due to incorrect and biased advice.

Fieldbus standards work with the British Standards Institution afforded an insight into the development of standards and their ramifications during a very busy period. Contributions and corrections concerning various technologies to a fieldbus guide that the market desperately needs (according to the manufacturers represented at the committee), have been made.

9 Present and future trends

9.1 Control system architecture

Control systems have evolved from centralised monolithic PLCs, to decentralised hierarchical PLC control and recently to distributed stand alone or networked small, low cost PLCs. The availability of low cost PLCs has encouraged their use in areas that had previously been considered too expensive or impractical. Devices are now emerging with more intelligence and fieldbus support, enabling peer to peer communications in a highly distributed control architecture. These devices can be programmed to act independently and co-ordinate/control other devices. Future development predicted by Odo Struger suggests that control systems will become 'holonic', with devices acting autonomously in a co-operative fashion.[82]

The use of PC control will continue to grow, PC control was originally marketed by non-PLC manufacturers as an alternative to PLCs. Now with the increase in open fieldbus usage, there is a slow move towards open control systems based on industrial workstations, with the ability to support multiple fieldbus networks. The familiarity of personal computers and the ability to combine functions of a PLC, programming terminal and operator interface have cost advantages that encouraged the trend. This is a direct threat to traditional PLC manufacturers who have provided proprietary networks and subsequently a selective open fieldbus network strategy (Figure 8). These manufacturers, such as Rockwell, have started to offer PC based PLCs, offering the robustness of PLCs with the choice of PC software and PC based network interfaces, control software and complete industrial PC systems.

9.2 Integration of manufacturing & business systems

More intelligence is being embedded in devices, such as micro PLCs, HMI, motor drives and I/O (web servers) in a movement towards more distributed control, due partly to increasing processor power at reducing cost and the integration of technologies. The combination of fieldbus and Microsoft Windows CE for instance, will allow seamless integration enabling real time information to be easily available from the plant to the enterprise planning systems.

Object linking and embedding (OLE) for process control (OPC) offers a standard to connect control equipment and systems to networks and business systems. Use of OLE and component object model (COM) technologies (from Microsoft) present standard methodologies and interfaces for factory automation that allow reuse of interface development.[83] This facilitates the 'plug-and-play' of PC systems in a manufacturing environment. The first products available are HMI, SCADA, and controllers.[84]

9.3 Real-time Ethernet

The control architecture paradigm, composing plant, centre, cell, station and device has been reduced to three layers, information, control and device/sensor (or field). Most PLC manufacturers have provided Ethernet interfaces for communication between controllers and business systems. Only Ethernet and device networks have been used in some open control applications, flattening the network hierarchy further.[85]

There is a growing number of suppliers of Ethernet I/O devices for control level, due to its high speed and low cost, some with internet web server capability (such as Opto 22 Ethernet I/O) using TCP/IP. Various fieldbus organisations are developing fieldbus protocol enhancements in order that Ethernet can be used in place of control and device level networks. Those undertaking TCP/IP encapsulation include DeviceNet, ControlNet, Fieldbus Foundation, Interbus & Profibus DP. Encapsulation utilises the advantages of the network model, with Ethernet being used as a physical layer and transport mechanism.

These developments are anticipated to meet the increasing data requirements for process monitoring, which can be achieved at minimal additional cost by increasing the speed of Ethernet to 100 Mbps. The increase in speed will also reduce the likelihood of collisions, making the network appear more deterministic. Collisions can be eliminated by direct connection of devices to switching hubs (port switching), traffic on a portion of the network is then only to or from a device. This will eliminate some benefits that may be assumed from the office environment in the short term at least, such as low cost and wide availability.

Cost will no longer be comparable once the Ethernet media, interfaces and hubs have been industrially hardened. Ethernet has other disadvantages, it is more susceptible to noise, where fieldbus networks have been designed to operate in noisy industrial environments. It has a high overhead and does not utilise bandwidth as efficiently as fieldbus networks, hence the need to increase speed and segregate or limit networks. The Industrial Ethernet Association has been formed to address these issues by standardising messaging, interfacing, connectors and suitable deterministic architectures.[86]

9.4 Machine safety fieldbus

The development and introduction of safety-related fieldbus is set to revolutionise the machine safety market. The same benefits of the other fieldbus networks will be achievable, greatly reducing complexity in many systems and improving maintainability. The initial adoption rate of this technology is likely to be slow due to the fundamental change, with dated safety standards and an uncertain and possibly sceptical end user market.

10 Conclusion

Contributions have been made in the following areas:

10.1 Fieldbus selection & planning

Fieldbus selection has established appropriate criteria for evaluation of fieldbus. Network planning has given customers the ability to question the viability, suitability and benefits of various control system architectures and configurations prior to implementation. Enhancements to a network configuration tool (electronic data sheet) have been made to aid control system programming and the provision of comprehensive diagnostics requiring minimal user effort. A guide to fieldbus documentation has been developed to provide clear, consistent, high quality device manuals.

10.2 Application case studies

Quantifiable benefits of fieldbus have been identified by the assessment of fieldbus implementations. Work performed on the fieldbus demonstrator highlighted many of these key benefits. These benefits have been disseminated to potential users and quoted in the BSI fieldbus guide.

10.3 Fieldbus demonstrator

Companies considering the use of fieldbus technology can see the advantages and functional interoperability of devices from many different manufacturers on the unique fieldbus demonstrator at Warwick. The facility has successfully shown the potential fieldbus technology can offer customer applications and clarifies end user confusion over network suitability.[87]

10.4 Transitory fieldbus connection

Complexity has been reduced and functionality increased by the novel use of fieldbus technology in transitory connections. The implementations have proven the concept, which cannot be achieved with all networking technologies.

10.5 Safety fieldbus

The first installation of a totally networked control application including safety has been completed. The safety-related fieldbus is still being thoroughly tested and evaluated. This revolutionary technology has been demonstrated to the Health and Safety Executive for their own evaluation.

The additional safety related features were determined for an existing fieldbus technology, to meet machine safety requirements. The research is the foundation of a function specification for safety-related system development by Rockwell.

10.6 Fieldbus standards

Many fieldbus implementers are now aware of the impact of legislation on fieldbus usage and the flawed use of standards to promote certain fieldbus technologies. The end user best interest and an unbiased perspective have been conveyed through Membership of the Advanced Manufacturing Technology (AMT/7) Committee (monitoring and control aspects of AMT) of the British Standards Institution. The 'Guide to the evaluation of fieldbus specifications – selecting the best for your application', a forthcoming publication by the BSI, has been prepared by the same Committee. Contributions to the publication include the glossary, technical specifications of various technologies and benefits from fieldbus case studies.

11 Glossary

ASi	Actuator Sensor interface
BIA	Berufsgenossenschaftliches Institut fur Abeitssicherheit, German certification body
BSI	British Standards Institution
CAN	Controller Area Network
CANopen	device level network based on CAN technology
CEN	European Committee for Standardisation
CENELEC	European Committee for Electrotechnical Standardisation
CiA	CAN in Automation
DeviceNet	device level network based on CAN technology
EN	European Norm (standard)
EDS	Electronic Data Sheet
Ethernet	local area network
FF	Fieldbus Foundation
FIP	Factory Automation Protocol
FTS	Flexible Tooling System
HMI	Human/Machine Interface (operator interface)
HSE	Health and Safety Executive
HTML	Hypertext Mark-up Language
I/O	Input/Output (to/from a controller)
Internet	global computer network
Intranet	Internet technology deployed inside an organisation
IEC	International Electrotechnical Commission
ISO	International Organisation for Standardisation
LAN	Local Area Network
Ladder logic	programming language for PLCs (based on relay logic)
LONWorks	Local Operating Network
MIS	Management Information System
MMI	Man/Machine Interface (operator interface)
ODVA	Open DeviceNet Vendor Association
OEM	Original Equipment Manufacturer
OLE	Object linking and Embedding
OPC	OLE for Process Control
PC	Personal Computer
PLC	Programmable Logic Controller
RFID	Radio Frequency Identification
prEN	proposed European Norm (standard)
Profibus	Process Fieldbus
PTO	Profibus Trade Organisation
Safetybus p	(machine) safety-related fieldbus based on CAN technology
SALVO	Structurally Advanced Light Weight Vehicle Operation
SCADA	Supervisory, Control and Data Acquisition (software)
SDS	Smart Distributed System, device level network based on CAN
SIL	Safety Integrity Level
SoftPC	programming software for PC based controllers
SoftPLC	PC based controller (an alternative to a PLC)
SPC	Statistical Process Control
TCP/IP	Transmission Control Protocol/Internet Protocol
UML	Unified Mark-up Language
XML	eXtensible Mark-up Language

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