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ISO 11783: An Electronic Communications Protocol for Agricultural Equipment

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The Lecture Series has been developed by the Power and Machinery Division Tractor Committee (PM-47) of ASAE to provide in-depth design resource information for engineers in the agricultural industry. Topics shall be related to the power plant, power train, hydraulic system, and chassis components such as operator environment, tires, and electrical equipment for agricultural or industrial tractors or self-propelled agricultural equipment.

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ISO 11783: AN ELECTRONIC COMMUNICATIONS PROTOCOL FOR AGRICULTURAL EQUIPMENT

During the past decade, manufacturers of agricultural equipment have increasingly turned to electronics to provide products with improved functionality, productivity, and performance to customers. Electronic content in agricultural equipment has increased. A natural consequence of adding electronic components to agricultural equipment has been realization of the advantages of allowing the components to communicate. A hitch controller on a tractor, for example, may communicate with a transmission and engine controller to allow optimized performance. Electronic communications can be used to coordinate machine components, allow information to be shared among components of a machine, and allow control systems to be distributed across components of a machine. The cost of adding communications is a small part of the cost of stand-alone electronics, but may add significantly to the functionality, productivity, and performance of the machine.

The interface between tractor and implement required significant standardization with development of standardized PTOs, hydraulic connections, and three-point hitches. This standardization enabled equipment designed by various manufacturers to be used together. Addition of electronics to agricultural machines has created a similar requirement and need for additional standardization. A requirement for communications between implements and tractor mounted displays and other tractor mounted components underscores the need for a standardized electronics communication protocol. The trend toward increasing use of out-sourcing in agricultural equipment manufacturing is also a factor in the need for a standard communication protocol. Components added to equipment from different OEM manufacturers must also inter-communicate. Without a standardized communications protocol, OEM suppliers must build to satisfy the proprietary protocols of each manufacturer. The cost savings of common components and software would be lost without a standardized communications protocol.

Electronic communications require significantly more standardization than was needed in earlier tractor implement interface standards. Not only must the physical compatibility be addressed, but compatibility in the way information is communicated must be addressed. To communicate ground speed for example, connectors, wiring, voltage and current levels, and the methods of signaling information must be compatible. Information can then be communicated, but agreement must also exist with regard to the encoding of the information and the definition of the information. With ground speed, the units of measurement, precision, definition, and frequency of measurement must be agreed upon for it to be interpreted. An impact of standardizing a communication protocol for agricultural equipment is also to standardize the definitions and representations of variables associated with agricultural equipment.

The rapid development of interest in precision farming has also increased the need for a standardized electronics communications protocol. Precision farming systems imply gathering of information which characterizes soils and crops and use of that information as feedback to better manage application of fertilizers and chemicals, and to adjust cultural practices. Communications between equipment operators and implements and between management information systems (MIS) (generally office or home computers in the context of current precision farming systems) and field implements are essential functions in precision farming systems. Elements of these systems include operator displays or terminals and an interface which allows MIS data to be communicated to and from implements. These elements are typically located in the cab of a tractor or combine harvester and must have a communications link to implements or other components of the machine. Standardized representation of variables associated with the equipment is necessary. A standardized electronic communications protocol is needed and can be the same protocol as that used among other parts of the machine.

ISO 11783 is a new standard for electronics communications protocol for agricultural equipment. This standard has been developed to meet the needs for electronic communication between tractor and implements, between components within tractors, within implements, and within other self-propelled agricultural machines. Support for precision farming applications have also been built into the standard. Definition and support exists for operator interfaces, and communications with an off-board management information system.

The purpose of this article is to provide an introduction to ISO 11783. Some background and history of the

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standard's development is provided. Critical design issues associated with implementation of ISO 11783 are reviewed. In addition some example information regarding ISO 11783 designs is provided, and some speculation is included regarding future applications of ISO 11783.

INTRODUCTION

Information display and control systems have evolved throughout the development of agricultural equipment. Adjustment and control of the equipment to suit crop needs is an essential function. Mechanical control and display systems have been integral to agricultural equipment and continue to provide function today. An example is in ground driven seed metering systems on seed drills and planters. As more capabilities have been added to agricultural equipment, additional control systems have been added to allow regulation of these capabilities. The addition of hydraulic three-point hitch systems for example, was accompanied by controls and information display systems for hitch height. Electronics have been added to agricultural equipment primarily to augment both control and display capabilities. Electronic engine controls have been added to control fuel systems and provide improved engine efficiency and reduced emissions. Similarly, electronic transmission controls allow improved control over shifting.

A natural consequence of adding electronic controls to the engine, transmission, and other machine components is the need for communication between the controllers. Torque and speed information is needed by the transmission for shifting, and fueling commands are needed by the engine to allow shifting. Concurrently, display of engine and transmission status to the operator is required. A central control unit could be used but wiring would be complex, reliability compromised, and computational capability inadequate. An alternative strategy currently in use is to distribute each of the controllers to service the function they control. This simplifies development, allows cost effective performance, and can simplify wiring harnesses, but presents the problem of intercommunication between controllers.

Tractor to implement communications are a case where wiring is significantly simplified by using distributed controllers. Controllers on-board an implement and the display and MIS interfaces in a tractor are naturally distributed. A communications link among implement and tractor mounted electronic control units (ECUs) which spans the hitch from tractor to implements is necessary and should minimize the number of wires that must cross the hitch.

Multiplex wiring has evolved to accommodate cost effective communications among ECUs. In this wiring scheme, a single pair of wires, a bus, is shared among controllers and used to carry logical "1" and "0" signals or bits as shown in figure 1. Groups of bits are sent as messages with the first bits of the message forming an identifier for the message. The protocol embedded into the ECUs requires the ECU to check the bus to assure no other ECU is using it before transmitting. The strategy works because enough free time exists on the bus for all of the ECUs to pass their messages without significant delays.

Figure 1–Multiplexed wiring

ISO 11783 standardizes a multiplex wiring system as described above, based on the Controller Area Network (CAN) protocol developed by Bosch (Bosch, 1991). This protocol uses a prioritized arbitration process to allow messages access to the bus. When two messages are sent at the same time, their identifiers are imposed bit-serially onto the bus. The bus must be designed to allow dominant bits to overwhelm recessive bits when both are applied simultaneously by different ECUs on the bus. No conflict occurs as long as the ECUs are sending the same bits, but when one sends a recessive bit while the other sends a dominant bit, the bus state is dominant. The ECU sending the recessive bit must sense the bus is at a dominant state when the bit was sent and must cease transmitting the message at that time and retry the next time the bus becomes idle. This strategy allows more dominant identifiers, those with a lower value, to have a higher priority on the bus. To allow this feature to work properly, CAN synchronizes messages at the beginning of each transmission to assure bits are aligned. The result is that ISO 11783 provides a communication system where ECUs share a communications link, and messages at any point in time are allowed access to the bus based on their priority.

Adoption of multiplexed wiring opens many opportunities with regard to coordination of control systems on-board agricultural equipment. Once multiplex wiring systems are available, the cost to share most information among controllers becomes very low. The limiting constraint is the volume of information that may be shared, given the communications bus has limited capacity.

HISTORY

Multiplexed wiring systems based on proprietary designs have been used in agricultural equipment for many years. Early examples include the Chrysler Collision Detection (CCD) based network used on Deere equipment. The Deere 7000 series tractor introduced in 1992 incorporates a network which may have as many as five ECUs controlling various aspects of the tractor. Deere has used this network in various types of their equipment. New Holland reported use of a CAN based network on their Genesis™ series tractors in 1994 (Young, 1994). Genesis uses four ECUs to handle the right hand console, instrument cluster, transmission control, and draft control. Caterpillar's Challenger™ 75 and 85 series tractors includes an SAE J1587 data link (Lubbering and Smith, 1993). Early applications of networks in implements have also been reported. Flexi-Coil reported the use of an SAE 1708 based network on their air seeder monitor and control system in 1993 (Weisberg et al., 1993). Flexi-Coil's system included a cab and remote implement ECUs with provisions for as many as 18 ECUs. The application of network based control systems for product application was patented by Ag-Chem Equipment Company Inc. in 1995 (Monson et al., 1995) and was later introduced in their Falcon™ series application systems.

The potential that exists for beneficial application of networks in agricultural equipment was recognized at ASAE in the mid 1980s (Bernard, 1986; Searcy and Schueller, 1986; Artman, 1986; Stone, 1987). At that time the same authors also recognized the critical need for standardizing communications interfaces for agricultural equipment. The catalyst that eventually focused standardization activity within North American industry were the efforts within Germany to create an international standard for an agricultural equipment communications network. By mid 1988, a committee in Germany formed under the LAV (German Farm Machinery and Tractor Association) and selected CAN version 1 as a basis for a new standardized agricultural bus, LBS (Auernhammer, 1983). The DIN 9684 data bus system (LBS) development efforts were reported by Schueller at ASAE in 1988 (Schueller, 1988). By 1991, the development work in Germany was well along and Germany had requested that ISO begin an effort to standardize an agricultural bus system. Drafts of the five part DIN 9684 were made available to ISO TC23/SC19 (Technical Committee 23 — Tractors and Machinery for Agriculture and Forestry, Subcommittee 19 — Agricultural Electronics) in October 1991. Subcommittee 19 was newly formed in early 1991 and included a working group, WG1, with a work item to focus on development of a standard for a “data bus system”.

In North America in early 1991, a combined group was organized to represent agricultural equipment industries, composed of the ASAE 353/1 subcommittee (Mobile Communications Systems), and the SAE ORMTC/SC32 subcommittee (Off-Road Machinery Technical Committee/Electronic Control and Monitoring Systems) coordinated through the Equipment Manufacturers Institute (EMI). This group eventually named itself the Construction and Agriculture Multiplexing Task Force. The Con. Ag. Multiplexing Task Force charged itself to develop a serial communications protocol standard that would meet the needs of North American agricultural and construction equipment manufacturers and to conform to and/or influence the developing ISO and SAE standards. In particular, the task force was well aware of the developing SAE J1939 standard and was committed to developing an ISO proposal that would be compatible with SAE J1939. The Con. Ag. Multiplexing Task Force focused efforts on development of a proposal for a serial communications protocol standard. The task force hired consultants, gathered the appropriate information, and produced a draft proposal by summer 1992. The Con. Ag. Multiplex Task Force sought compatibility with SAE J1939 and was accepted as a Task Force of the SAE Truck and Bus Electronics and Control Subcommittee (the developers of SAE J1939) in June 1992.

The ISO working group initially met in February, 1991, and began work on an interim connector standard (ISO 11786). By February 1992, significant discussion of an agricultural data bus had begun and at that time the working group agreed to adopt the use of CAN 2.0b, a recently introduced CAN specification. By summer 1992, proposals from the UK, the US, and Germany were being considered by the working group.

Since 1992, ISO TC23/SC19/WG1 has continued development of the communications protocol standard (ISO 11783). The standard now consists of 10 parts, which specify various aspects of the network as identified in table 1.

The various parts of ISO 11783 are derived from SAE J1939, DIN 9684 or have been developed within the working group (WG1) as shown in table 2. ISO 11783 relies on SAE J1939 derived components for the basic communications structure with applications largely derived from DIN 9684. Some components of the standard are being developed wholly within the working group rather than being drafted at DIN, ASAE, or SAE. This process, while requiring large amounts of the working group’s time, diminishes the time required to convince working group members to adopt a particular national standard and then adapt that standard to all member’s needs.

Many of the changes and new requirements developed within the working group regarding DIN 9684 and SAE J1939 have been passed back to the respective national groups and have resulted in modification of both standards. The elements of DIN 9684 and of SAE J1939 that are being used in ISO 11783 have now been balloted and published by their respective standards organizations. Both standards are documented in the literature; SAE J1939 by Stepper (Stepper, 1993; Stepper et al., 1995) and DIN 9684 by KTBL (KTBL, 1983). Currently, all documents within

Table 1. ISO 11783 documents and their scope

ISO 11783 Part	Title	Scope
1	General standard	Provides an overview of the standard and describes how the parts are used together.
2	Physical layer	Specifies the wiring, connectors, and the physical representation of signals on the bus.
3	Data link layer	Specifies the way information is structured in CAN message frames and specifies methods for transmitting messages longer than a CAN message frame.
4	Network layer	Specifies how multiple sub-networks may be interconnected.
5	Network management	Specifies methods for initialization, and a method for unique naming of computers within the network.
6	Virtual terminal	Specifies a device which may be used by an operator to interact with computers on the network.
7	Basic implement messages	Defines messages that may be used in tractor/implement communication
8	Drivetrain/application layer	Defines messages that may be used throughout a vehicle and contains messages for drivetrain control.
9	Tractor ECU	Defines the functions of a tractor on the network and communications between drivetrain components on the network and implements
10	Task controller & management computer interface	Specifies communications within a management computer between a task controller interface and applications software.

Table 2. ISO 11783 document relationships and status

ISO 11783 Part	Title	Primary Document Source	SAE J1939 or DIN 9684 Title	Current ISO Status and Date	Planned ISO Status and Schedule
1	General standard	WG1	Base level document	Working draft	Committee draft, Spring 99
1	General standard	WG1	Construction and agriculture base level document		
2	Physical layer	WG1	Physical layer, twisted quad	Draft international standard (1997)	
2	Physical layer	SAE J1939-13	Diagnostic connector		
3	Data Link layer	SAE J1939-21	Data link layer	International standard (1997)	
4	Network layer	SAE J1939-31	Network layer	Draft international standard (1997)	
5	Network management	SAE J1939-81	Network management	Draft international standard (1997)	
6	Virtual terminal	DIN 9684	Virtual terminal	Working draft	Committee draft, Fall 98
7	Basic implement messages	WG1	-	Working draft	Committee draft, Fall 98
8	Drivetrain/application layer	SAE J1939-71	Applications layer	Working draft	Committee draft, Fall 98
9	Tractor ECU	WG1	-	Working draft	Committee draft, Spring 99
10	Task controller & management computer interface	DIN 9684	Management computer interface	Working draft	Committee draft, Spring 99

ISO 11783 are scheduled to be passed forward to SC19 by the end of 1999 at which point the final balloting process will begin.

Related work is underway at the Agricultural Electronics Association. This association was created in 1995 and includes a Software and Information Systems Council that has been working on exchange of computerized agricultural data, particularly agricultural data with spatial content. They have created guidelines for exchange of yield data, soil fertility data, and application planning data between precision farming applications. This work is related to the Task Controller & Management Computer Interface, Part 10 of the ISO 11783 standard. ISO 11783 Part 10 defines the data format for exchange of information between precision farming application software and task controller interface software as shown in figure 2.

Equipment based ISO 11783 requirements has begun to appear on the market. The equipment in general can not advertise full 11783 compliance until the standard is complete, but some parts of the standard are complete. Most parts are now near completion, allowing proprietary systems that are partially compliant. Examples of systems currently on the market are the Case MX series Magnum™ tractor, Flexi-Coil's FlexControl seeder and sprayer controllers, and Deere's Greenstar Precision Farming System.

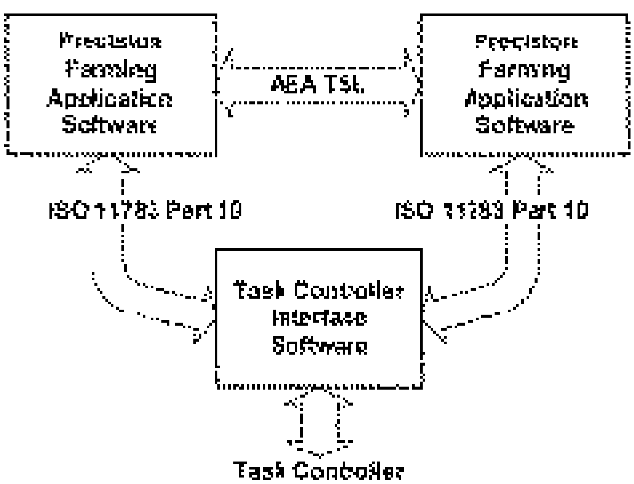

Figure 2–Data exchange between software components on management computers. (TSL refers to the AEA's Transfer Support Layer)

ISO 11783 Overview

ISO 11783 has been written to support applications of networks in agricultural equipment. The scope of the ISO committee responsible for the standard includes forestry equipment, but does not include construction equipment. The standard could be applied more broadly, but no specific support beyond agricultural applications has been provided. The standard supports application on both self-propelled systems and in tractor-implement systems. A tractor-implement model is assumed throughout the documents, with the recognition that the same or a simpler design can be used in self-propelled systems. Figure 3 shows in schematic form a simplified ISO 11783 Network superimposed on an agricultural tractor and implement background. A network with no master controller has been defined. The network is composed of two communication busses, a Tractor Bus and an Implement Bus. The Implement Bus spans the tractor, crosses the hitch, and spans implements. The implement is shown in this schematic with an implement sub-network. The busses are interconnected with network interconnection ECUs, the Tractor ECU and an ECU labeled "Implement ECU and Implement Bridge". The characteristics of the Tractor ECU are specifically described in ISO 11783 Part 9. A Task Controller and Management Computer Gateway and Virtual Terminal (labeled "VT") are shown connected to the Implement Bus. The Virtual Terminal is described in Part 6 and the Task Controller and Management Computer Gateway are described in Part 10 of ISO 11783. The Task Controller is an ECU which normally resides on the tractor and is used to provide commands to implements to accomplish some task. An example might be to provide the commands of a prescription in a precision farming operation. The Management Computer Gateway portion of the Task Controller and Management Computer Gateway contains an interface that is compatible with the

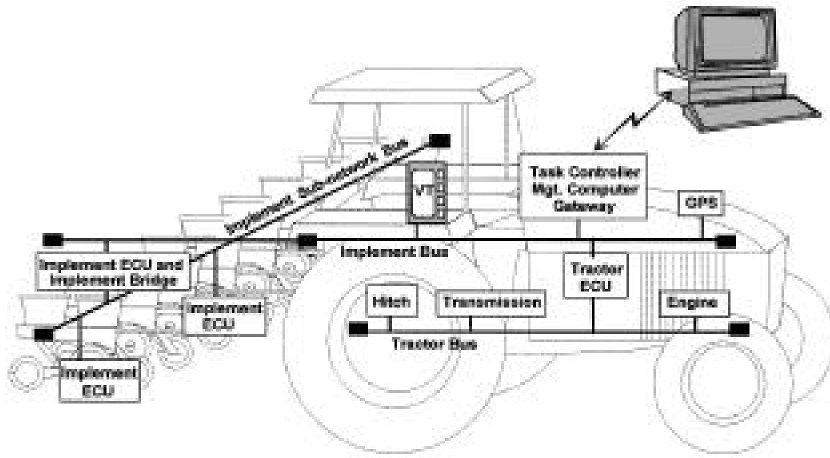

Figure 3–Schematic of an ISO 11783 network on an agricultural tractor

Management Computer and allows data to be exchanged between the Task Controller and the Management Computer. Standardized communications are defined between the Task Controller and implements and between the Task Controller Interface and applications software on the Management Computer as described in figure 2 above. The interface between Management Computer and Task Controller is not standardized.

The network has messages defined to allow communications between any of the components (see fig. 3). An example might be communication between the Task Controller and the GPS ECU. Navigational messages are defined and allow positional information to be received by the Task Controller. In the same sense, messages are defined to allow the Engine ECU to provide a current torque curve to the transmission. Information sharing as just described is supported as well as control messages. Some messages are defined with repetition rates of 100 messages per second. This type of message utilizes approximately 5% of the bus capacity, with conservative maximum average bus use targeted at approximately 35%. Many messages are currently defined with various repetition rates, and careful planning has been necessary to prevent overuse of the available bus capacity. The Tractor ECU provides filtering of messages between the tractor and implement bus. This filtering is necessary to prevent heavy traffic on either bus from overloading the other. Support of precision farming applications across the implement bus has been included in ISO 11783 as well as support for implement and tractor coordination.

Flexible expansion of the communications in ISO 11783 has been implemented. The network supports the use of proprietary communications simultaneous with standardized messages. Manufacturers are free to implement enhanced control and information systems beyond those directly supported in the standard. A process has also been included in the standard to accommodate requests to expand the message set beyond that currently defined.

ISO 11783 does not provide a complete design that can be implemented without further considerations on agricultural equipment. A goal of the committees writing the standard was to standardize only those aspects of communications protocol that must be standardized. This approach leaves to designers the responsibility of assuring that overall design requirements are met. Management of a break or failure of the communications bus must be a part of a system design and ECUs should be designed to accommodate that failure gracefully. Similarly, though the standard has been specified to allow designs to meet applicable EMC (Electromagnetic Compatibility) requirements, designers must assume the responsibility of assuring their designs based on the standard meet those requirements.

COMPONENTS

A basis for understanding ISO 11783 networks can be gained through examining the components that compose a network. Logical and physical components of the network are described below.

WIRING AND CONNECTORS (THE PHYSICAL LAYER)

A "twisted quad" cabling system was developed especially for ISO 11783 networks. Selection of a bit rate to be carried in the cabling system had considerable influence on the design. 125 K bits/s was considered roughly the fastest rate that could be handled without a shielded cable while producing acceptable EMC performance. A 250 K bits/s shielded twisted pair specification was available in the SAE J1939 documents (SAE J1939/11) but shielding was regarded as unacceptable by manufacturers. DIN 9684 included a 50 K bits/s un-shielded design, but the bit rate was considered too low for the applications anticipated by manufacturers. An unshielded 250 K bit/s design with carefully selected voltage slope (dv/dt) and approximate current control in the data lines was proposed by Deere. This design was proven and is being adopted as Part 2 of the 11783.

The twisted quad cabling system uses four wires enclosed in a jacket as shown in cross-section in figure 4. Two of the wires are used to carry data, CAN_H and CAN_L, and two (TBC_PWR and TBC_RTN) are used only to provide power to terminators at the end of the bus as shown in figure 1. The terminator requirements and the method of powering the terminators are rigorously specified in the standard. ECUs are connected to the bus as shown in figure 1. The TBC (Terminating Bias Circuit)

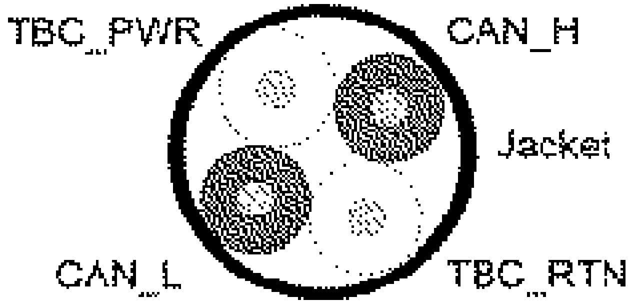

Figure 4–Cross section of the twisted quad cable (ISO, 1998a).

lines are included in the cable at all points, but are not connected within an ECU.

The Part 2 specification has been written to allow use of some ISO 11898 integrated circuit bus drivers to be used in ECUs. These integrated circuits are readily available at reasonable cost though discrete designs may also be used and may provide enhanced EMC performance.This feature provides the opportunity for ECUs designed to meet SAE J1939/11 to be connected and operate within an ISO 11783 bus system, though slope control must be set within these ECUs to prevent EMC problems.

Termination of the bus at both ends is a requirement. This presents some problem at the hitches of a tractor. When an implement is un-hitched and there are ECUs operating on the tractor portion of the implement bus, un-hitching could result in the tractor portion of the bus being un-terminated. A special automatic terminating Bus Breakaway connector has been developed to solve this problem and is specified in the Part 2 document. This connector is designed for the tractor at hitching points, and automatically applies termination when an implement is un-plugged. Use of this connector is also encouraged at any points where implements are regularly hitched and un-hitched from each other.

The Part 2 document specifies three standard connectors; Bus Breakaway, Diagnostics, and Bus In-Cab connectors. Figure 5, taken directly from Part 2 shows a connector use map. The physical specifications of the Bus In-Cab connector are given. It can be used for adding components to the bus in the cab of a tractor, for example, virtual terminals and task controllers. The linear nature of the bus must be maintained when using the In-Cab connector, requiring that a new section of bus be added when adding a new component. A diagnostics connector is also specified in Part 2 and is provided for diagnosis of both the tractor bus (if it exists) and the implement bus.

The selection of a bus topology as shown in figure 3 places a restriction on some applications. The maximum length of a single segment of the bus is 40 m. ECUs may be connected to the bus at any point (not closer than 0.1 m of each other), but the length from the bus to the ECU must not exceed 1 m. This topology prevents configuring the network as a “T” or cross. An example might be on an implement where the bus traverses an implement from front to back, and there is a need to extend the bus more than 0.6 m side to side. In this case either a serpentine arrangement of the bus must be used or a network

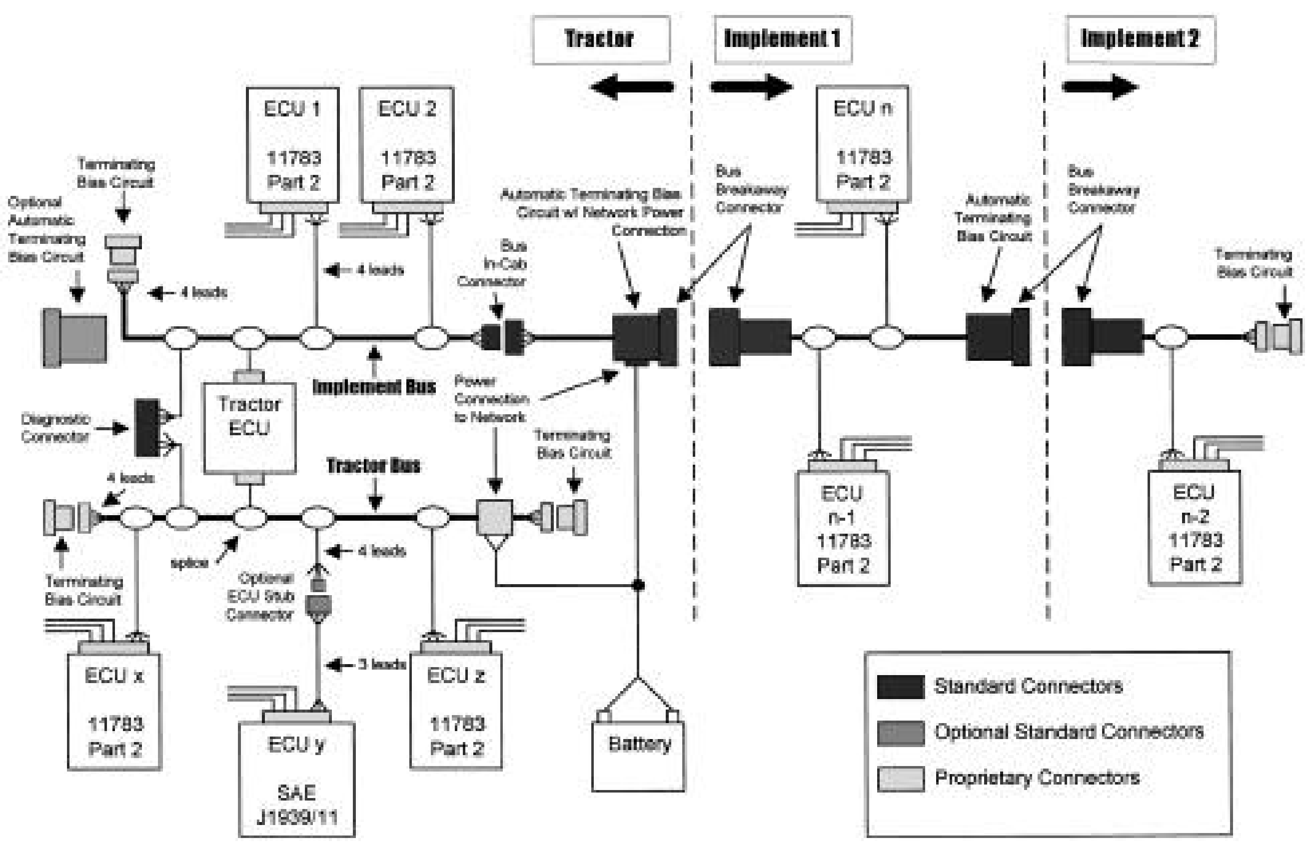

Figure 5–Connector use within ISO 11783 (ISO, 1998a).

interconnection device must be used with an implement sub-network as shown in figure 3.

Constraints exist for the number of ECUs that may be connected on a single segment of the bus. A maximum of 30 ECUs may be connected on a single segment. Multiple segments may be interconnected with bridges allowing up to 254 ECUs in a system.

MESSAGE STRUCTURE (THE DATA LINK LAYER) — 29 BIT CAN

ISO 11783 is based on the use of the CAN 2.0b 29 bit protocol (Bosch, 1991). This protocol is designed to send bits serially as described earlier. A single frame or collection of bits sent by a CAN controller is shown in figure 6, and consists of an identifier and a data field. Many additional bits (not shown in fig. 6) are defined in the frame for use in the CAN protocol controller, including cyclical redundancy check bits which are used to allow receivers to determine if the data frame sent was received without bit errors. Undetected errors are confined in the CAN protocol to a probability of less than 4.7×10^{-11}.

ISO 11783 defines the interpretation of the 29 bits in the identifier of CAN frames as well as the interpretation of the data. Two types of identifier structures, or protocol data units (PDU), are defined. Figure 7 shows a schematic of the definition of the identifier bits for both types of identifier structures. In both types of PDUs, the least significant 8 bits define a "source address". This value is a physical address of the ECU sending a message. The first three most significant bits of the identifier are defined as independent priority bits. Recommendations are provided for the values of these bits in the standard, but they may be adjusted by a manufacturer in a particular application. The difference between the two PDU types is the inclusion of a destination address in PDU type 1. This message type allows the message to be sent to a particular ECU based on physical address. Addresses 0 through 253 may be used by an ECU, while 254 (the null address) must be un-used and 255 as a destination indicates a message to all ECUs (Global). The remaining portion of the identifier in each PDU is used to identify the Parameter Group in the data field, that is, the content of the data field which may be defined to contain multiple parameters. This remaining portion of the identifier is used to compute a "Parameter Group Number", a unique numeric identifier for each group of parameters that may be contained in the data field.

Figure 6–Components of a CAN frame.

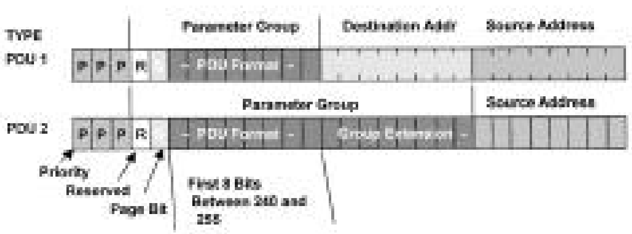

Figure 7–Interpretation of the identifier of CAN frames in ISO 11783.

ISO 11783 messages are defined to allow any Parameter Group to be sent from any ECU. The inclusion of a Source Address in the identifier is used to guarantee uniqueness of the identifiers in the system, a requirement of CAN. This requires that addresses of ECUs in the system be set to unique values.

General purpose messages are defined in ISO 11783 to allow a request to be made for a particular Parameter Group. The use of the remote transmission request (RTR) feature of CAN is not defined for ISO 11783. A general purpose message is also defined to allow acknowledgment or negative acknowledgment of a message. The use of acknowledgment is defined for each message.

Messages in ISO 11783 are normally composed of a single CAN frame, but can be composed of multiple frames. Two types of multi-frame messages (Transport Protocol) are defined; 1) a Broadcast Announce Mode message, where an initial frame is sent announcing the specifications on the frames to follow, followed by the rest of the frames, and 2) a Connection Mode message which is sent to a specific destination and allows the receiver to control the flow of messages being sent.

INTERCONNECTION STRUCTURE (THE NETWORK LAYER)

Though not a requirement, most ISO 11783 systems will have interconnected bus segments. The tractor-implement system shown in figure 3 is an example. A bridge must be used if transparent communications are to occur on interconnected ISO 11783 bus segments. Bridges use a protocol controller to connect to each segment and pass messages between the segments. A repeater which may not be used, simply echoes the electrical signal from one segment to the other. Limitations on bit timing in ISO 11783 prevents use of repeaters. The tractor ECU in an ISO 11783 network provides normal bridge functions, but normally has additional special functions defined in the Part 9 document.

ISO 11783 defines filtering capabilities for network interconnection ECUs. Provisions are made for these ECUs to prevent messages from being passed from one sub-network to another. Part 4 defines the structure and makes provisions that allow messages to be used to configure the filtering of messages. This capability is important in controlling network loading of bus segments. An example can be seen in figure 3 on tractors where a tractor bus and an implement bus coexist. The tractor bus is likely to have heavy loading with engine, transmission, and hitch messages. Most of these are not of interest on the implement bus and can be filtered from the implement bus by the Tractor ECU. In the same sense, messages to control setpoints on seeding rate on a seeder are generally not of interest on the tractor bus. Traffic partitioning performed by network interconnection devices can be used to control bus loading. Generally, manufacturers will need to configure network interconnection ECUs to optimize performance of their systems.

Some constraints exist on the way network segments may be interconnected and on the timing in network interconnection ECUs. Any segment may not be connected to another segment in more than one place. This precaution prevents loops in the network and the associated duplicate messages.

ADDRESSING, NAMEING, AND INITIALIZATION

ISO 11783 Part 5 includes requirements for a unique NAME to be included within each ECU. The NAME must be unique within a system and is a 64 bit value defined as shown in figure 8. The NAME is divided into two distinct parts, an upper 32 bits which is used to provide a functional name and a lower 32 bits which provides a unique code based on the ECU manufacturer and an identity number. Manufacturers must obtain a manufacturers code by request to the working group in order to build ECUs compatible with the standard. The manufacturer may then assign unique identity numbers to each of the ECUs made.

An initial design requirement for the network was to allow peer to peer operation but provide a coordinated method to assure unique message identifiers. An 8 bit address included in all identifiers was selected to meet the requirement. This feature, allows 254 ECUs to be connected in a network. Simple assignment of addresses to all of the possible ECUs based on their type appeared impossible, particularly for implement systems. Many components in a network can have an address assigned, a primary engine, or a primary transmission for example, but ECUs that are temporarily connected would have the potential of having conflicting addresses assigned. This problem was managed by providing both self and non-self configuring ECUs. ECUs in the network attempt to claim an address upon power-up. In the case of ECUs that are self-configurable, if they happen to claim a used address, an arbitration process occurs and the ECU with the lower valued NAME retains the address. Non-self-configuring ECUs always win an arbitration with a self-configuring ECU because the NAME includes a self-configuring bit that assures self-configuring ECUs have higher valued NAMEs. Non-self-configuring ECUs are expected to be configured with a tool during configuration of the vehicle and conflicts are resolved at that time. Agricultural implements must be equipped with self-configuring ECUs

The upper 32 bits of the NAME have capacity for functional naming of an ECU. These fields include an Industry Group field which is set to Agriculture for agricultural equipment. States are provided for Truck and Bus, Forestry, Construction, and Marine industries. The Device Class field is used to identify implements and the tractor and other similar systems. An instance field is provided for Device Class allowing multiple instances of implements. A Function field with capability for multiple instances is provided which may be used to define particular functions associated with ECUs. An ECU instance field is provided for cases where a single function instance may be split among several ECUs. Functions are not currently defined in ISO 11783, but an example of one type of function might be pressure control on a sprayer. Several instances of this function could be possible and it is possible that several ECUs might be used in a single pressure control system.

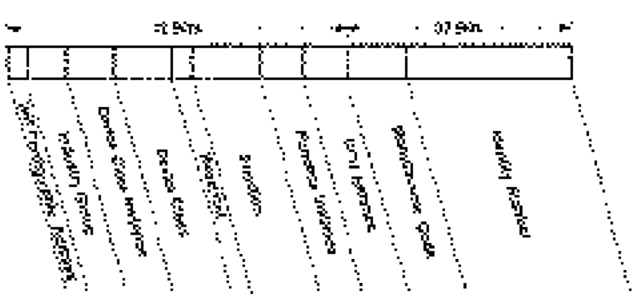

Figure 8–ISO 11783 NAME structure

VIRTUAL TERMINAL

The Virtual Terminal (VT) is an operator interface device provided to allow display of information to operators and to allow operators to provide input information. VTs are designed to be slaves of ECUs on the network. An ECU may secure service from a VT and then be able to display its screens and retrieve operator information for its purposes. The ECU will not necessarily be aware of other ECUs using the terminal, that is, the VT appears to be exclusively dedicated from an ECU's perspective. From an operators' perspective, the VT may be switched to display one ECU's information or another or both if the VT supports that capability. An example of the application of a VT would be with a sprayer as shown in figure 9 (ISO, 1998b). A sprayer could secure use of the terminal and display Spray Rate and Pressure. When the sprayer's panel is active on the VT screen, it has softkeys associated with the panel as shown on the right side of the screen in figure 9. The operator can switch to other panels which may be those of other implements.

The VT supports downloading of masks used to define panels displayed on the VT screen as well as alarm displays and softkey definitions for menus. The structured storage of masks in the VT is shown schematically in figure 9. Functions are also provided to allow masks to be loaded from or saved to some form of mass storage within the terminal. The ECU can simply instruct the terminal to load masks from mass storage and then select them for display.

Masks in a VT can contain output fields which are used to display on the screen and input fields which are used to retrieve data from an operator. Numeric data can be displayed on the VT by selecting a field for update, sending the data to the particular output field and selecting the field for end of update. The VT can format the data for display. In a similar sense, input from the operator can be obtained by selecting a field for input. When the operator has completed the input, data will be automatically sent to an ECU by the VT. Display from multiple ECUs can be coordinated from a single ECU. For example resources associated with several functions that may be in different ECUs as shown in figure 9 may be stored and selected in a coordinated fashion by the ECUs.

The VT specification supports both text and graphic displays. Graphic functions are included for line drawing as well as for higher level functions including bar and dial gauges. Bitmap graphic elements may also be defined and displayed.

TASK CONTROLLING

ISO 11783 supports a task control application. A Task Controller is contained within an ECU on the implement bus in the system. Commands may be loaded into a Task

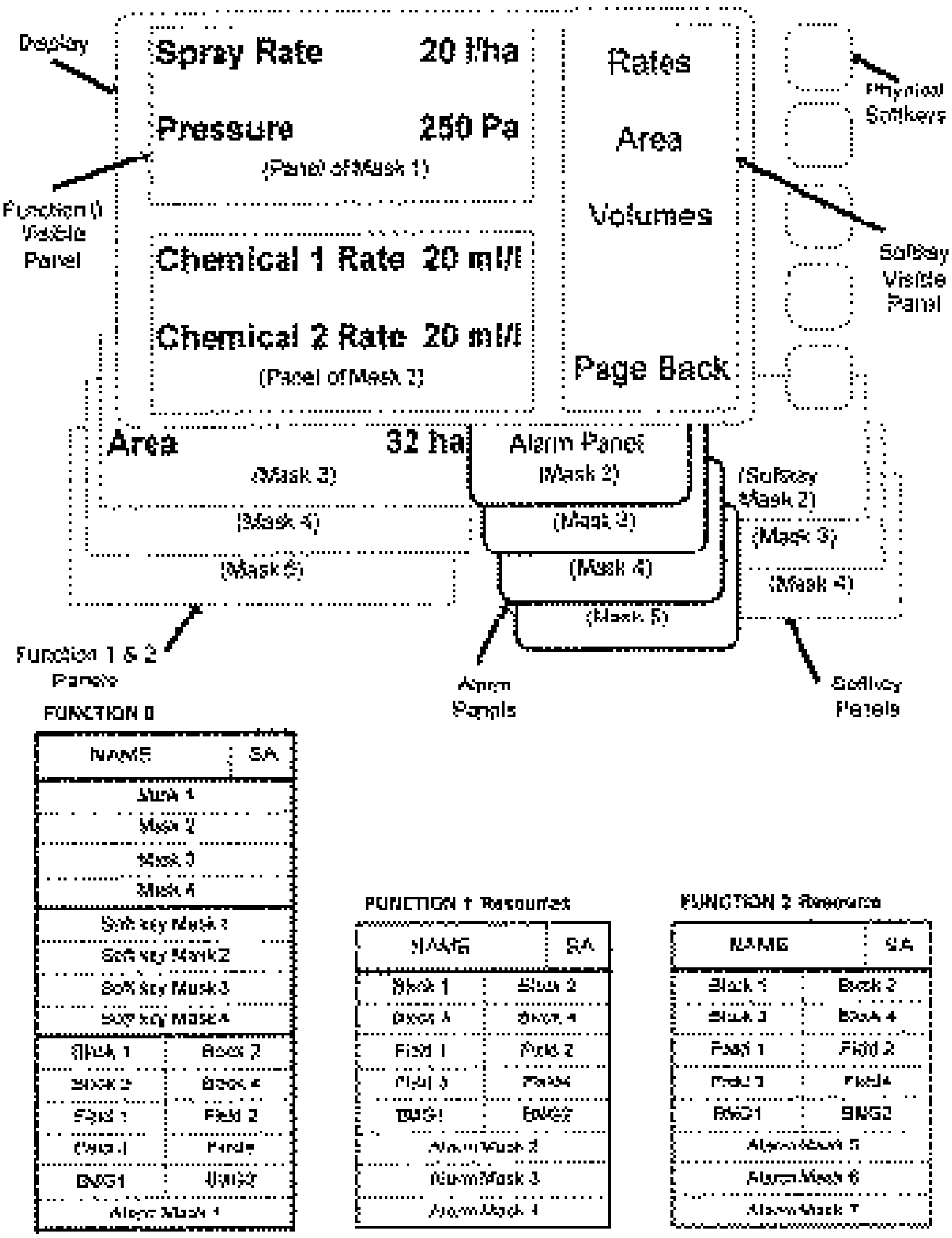

Figure 9–Schematic of a virtual terminal (ISO, 1998b).

Controller from a management computer before a field operation and then the commands delivered to a controlled device, an implement for example, during the field operation. Task Controllers support three modes of command delivery; time based, distance based, and position based. A common application of a task controller will be for use in precision farming systems. In that application, prescriptions created on a management computer can be transferred to the task controller. The task controller can then deliver the prescription to an implement as needed based on position measured by an onboard GPS system. Task Controllers also support the capability to log actual data during the field application and then transfer of that data back to the management computer.

A message was created in ISO 11783 Part 7 to allow commands to pass from task controllers to implements and from implements to task controllers. Figure 10 summarizes the field definitions in the message. The identifier contains a value in the R, G, and PDU Format fields that identifies the data field as the Process Data Message. The message

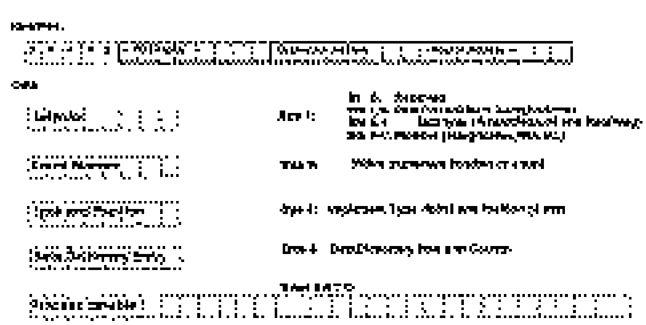

Figure 10–Field definitions of the process data message.

contains both source and destination address, allowing it to be sent to a particular ECU. If sent from a task controller to an implement, the message would be sent to the lowest instance of the Function being controlled within that implement. A single process variable is sent in this message in the four byte Process Variable data field. The selector indicates the data format of the variable, the type, and a Modifier, a qualification regarding the variable. The data type indicates whether the process variable is an actual value or a setpoint and whether the message is a request or a response (commands are sent as a response). The Count Number field allows specification of a particular element within the implement or may be used to select all elements. This may be a particular row, or bin depending on the process variable. The Implement-Type and Position field allows selection of a particular implement function, for example, a seeding function vs. a fertilizer application function within an implement. The position field allows selection of a particular instance or mounting position of that function. The Data Dictionary Field identifies the particular process variable which is a function of the particular Implement Type.

The Process Data message allows Task Controllers to send commands and query implements regarding their current setpoints and actual operating points. The same message allows implements to send current setpoints and actual operating points.

Tractor and Tractor ECU Messages

Messages have been developed to allow basic information to be available on the implement bus. These messages have been included in ISO 11783 Part 7 as listed in table 3. Most of these messages are sent repetitively at some rate fixed in the document and can be monitored by ECUs needing them on the implement bus. Others are sent on request, for example, Time and Date, which may be requested using the request message described earlier. An example of the use of these messages would be in an implement where seeding rate is being controlled. This implement could monitor speed and distance information and use that to regulate seeding rate.

Messages on the Tractor Bus

A set of messages are available primarily for use on the tractor bus. These messages include an extensive set for powertrain control and information as well as messages supporting service logging. This message set is defined in ISO 11783 Part 8 and is equivalent to SAE J1939-71. An example of these messages is the engine configuration message. This message communicates the current torque curve of the engine and could be used by an implement to optimize power use. A forage harvester could monitor engine power use with the Electronic Engine Control No. 1 message, and use the TC1 message to request a transmission gear settings to optimize forward speed and engine efficiency. This type of control system impacts safe operation of the vehicle and would require agreement between the forage harvester manufacturer and the tractor manufacturer. Tractors will likely be equipped with security mechanisms to prevent unauthorized command of critical functions on the tractor. This type of control could just as well be used in a self-propelled combine harvester to optimize performance.

Table 3. Basic messages included in Part 7

Message Title	Normal Source
Time and date	Tractor ECU
Wheel based speed and distance	Tractor ECU
Ground based speed and distance	Tractor ECU
GPS position and status data	GPS/navigation ECU
Attitude (bearing, pitch, roll, altitude)	GPS/navigation ECU
Hitch status (position and draft)	Tractor ECU
Power takeoff status	Tractor ECU
Auxiliary valve status	Tractor ECU
Hitch and PTO commands	Implement ECU
Auxiliary valve commands	Implement ECU
Lighting	Tractor ECU
Process data	Task controller/implement ECU
ECU power status and extension	Tractor/implement ECU

Diagnostics

Currently, diagnostics are not defined in ISO 11783, but the working group is discussing options. ISO 11783 does define a standard diagnostic connector (identical to SAE J1939) that provides connections to both the tractor and implement bus. This provides a standard physical connection point for data loggers and diagnostic tools. The VT also provides input/output capability that can be used to display and retrieve operator information for diagnostic purposes. SAE J1939 includes a diagnostic capability that is designed for use among network based ECUs and can be used with diagnostic tools. There is not agreement at this point regarding whether to include this or a similar capability in ISO 11783. Initial diagnostics are likely to be supported through proprietary diagnostic tools or through the VT.

Design Strategies for Implementation of ISO 11783

Guidelines for network development have been given by Young (Young, 1994) and example designs have been published (Stone, 1988). The guidelines by Young are summarized below.

1. Locate ECUs where concentrations of inputs and outputs exist.
2. Minimize the number of wires crossing critical boundaries.
3. Connect sensors or actuators to the closest module.
4. Locate ECUs so that critical closed-loop control is not performed over the network.
5. Condition, scale, and diagnose sensor or actuator information at the module to which they are connected.
6. Transmit information over the network in engineering units.
7. Make no assumptions about hardware or operator interface components connected to ECUs.
8. Broadcast data at a fixed rate.
9. Do not incorporate emerging standards until they are fully defined.

These guidelines are in general consistent with the current definitions in ISO 11783 and are suitable for examining addition of messages and parameters in the system. Some expansion and additions to Young's original guidelines are appropriate for ISO 11783 systems.

Location of ECUs to accommodate concentrations of input and output signals requires a survey of input and output signals in a proposed design. The survey should include identification of the signal, its physical location, its temporal frequency and temporal resolution, and its magnitudinal resolution and range requirements. Identification of magnitudinal resolution and range of signals should include classification of signals into digital or analog signals. Naming or identification of the locations about the machine should be done carefully before the survey is initiated, with the understanding that once defined, locations may be split or combined to allow allocation of signals to ECUs. Signals should be classified as setpoints or actual values, and as a measured or a status value. In the later case, an ECU might contain inputs where the status of a switch might be measured, for example a switch to turn the PTO ON or OFF. The same controller might also contain state data indicating whether the PTO is ON or OFF. Both signals may need to be communicated on a network and may not have the same value, for example the PTO switch is ON, but the PTO state is OFF because it may be inhibited for some reason. This is less a problem for actual values than with setpoints since the measured signal of an actual value is typically the same as the state signal.

Once a signal survey is complete, the signals should be compared to parameters that have already been defined in ISO 11783. Where possible, parameters should be communicated through messages that have been standardized. Signals that haven't been defined in ISO 11783 but appear to be generally needed by other manufacturers should be considered for standardization. A request to the ISO TC23/SC19/WG1 should be made to include these parameters and group them into messages. Those signals which must be communicated and are not candidates for standardization should be assigned to proprietary parameters and grouped into proprietary messages.

Identification of the ECUs needed in a system can be done after a signal survey is complete. An initial set of ECUs should be proposed for the locations about the machine and signals assigned to the ECUs by location. The signal count and total frequency of throughput should be constrained at each ECU to the reasonable capabilities that can be provided by an ECU.

Once the messages have been identified and the ECUs are known, the ECUs should be examined for computational capacity. The algorithms that must be executed within each ECU, the frequency at which it must be computed, and the memory space it will occupy must be determined. In addition, the load on the ECU to manage the network traffic it must handle must be determined. Both loads must be totaled and compared to the ECUs computational capacity. A re-allocation of signals to ECUs may be necessary, and once done, the load computation process repeated until a reasonable design is found.

Network load must also be examined as a part of the design. Total network load can be calculated or simulated based on the number of messages, their lengths, and frequency of transmission. The network load of each segment in the network should be calculated. A conservative target maximum load on each segment is approximately 35%. Larger loads should be considered carefully with regard to the impact on latency of messages. ECUs which are communications partners and contribute large loads may be partitioned to a separate subnetwork or combined to eliminate the network traffic.

Initialization processes of ECUs must be considered in the network design, This is particularly true for ECUs on implements or those communicating with implements. ECUs which may be disconnected and reconnected to the network without the use of a tool to readjust the address of the ECU should be configured to perform self-configuring addressing. In addition, in cases where more than one instance of these ECUs can exist on the network, some method must be provided to set the instance fields in the network NAME of the device. This problem exists with agricultural implements. Consider a planter that may be used alone or may be hitched side by side with several other planters. The planter may be manufactured and programmed initially to have a Device Class of "planter", and an instance of "1". When two planters are connected together some method must be provided by the manufacturer to set the instances of planter contained in the NAME in the ECUs. Several techniques are available, including a requirement that the components be connected and powered in sequence the first time they are used together. If this process is used, software must be included in a planter to detect other planters and to set its instance accordingly. In addition, some method must also be provided to allow the instance to be reset when the planter is configured differently. No specification is made in ISO 11783 regarding how instance setting is to be done, just that it must be done. Manufacturers must include resolution of this issue in their designs.

FAULT MANAGEMENT

Analysis and control of potential faults in machine design is a normal part of the design process. The use of an ISO 11783 network introduces opportunities for failures. Some that should be considered in an analysis include breaks in or shorts of one or more of the conductors in the communications bus. The Part 2 document identifies many of the potential failures in the bus wiring and the potential effect on communications. It is possible to continue communications in some cases where single bus lines are shorted or broken. In addition, the detection of the failure of the communications bus is being considered by bus driver manufacturers. Failures in communications can also be detected in the ECU through the CAN protocol controller. These devices typically provide indications of errors that occur in transmission and reception of messages. CAN includes an error recovery protocol which automatically re-attempts to send a message when a transmission error occurs. A mechanism is provided to prevent this from occurring indefinitely.

The probability of a undetected error can be calculated in CAN based networks based on the techniques used in protocol controllers for fault confinement. The probability of an undetected error in a CAN data link is 4.7×10^{-11}. If errors were detected at rates of 10 per second, the probability of a single undetected error occurring in a 10,000 hour life of a machine would be less than 0.02. Two conclusions can be drawn, first, that as long as errors do not occur at a high rate, it is unlikely that a single undetected error will occur within the life of a machine, and second, software should be designed to detect recurring errors in communications and to indicate a fault when the error rate is determined to be too high.

CAN is very effective in detecting errors in messages received, though, does not provide a robust mechanism to determine if a message has been completely missed or not sent in the first place. ISO 11783 provides definition of messages and that many of the messages be sent repetitively at a specified rate. It is up to designers to manage a failure to receive messages in an appropriate fashion.

Information that may be used in failure mode and effect analysis (FMEA) is provided in Part 2 and in the Bosch CAN 2.0 Specification (Bosch, 1991). The Part 5 document defines requirements regarding ECU operation during power drop-outs. ECUs must retain their information regarding network structure and continue to operate normally after a 10 ms power drop-out. No other significant requirements are made within the standard regarding actions that must be taken with a communications failure. Appropriate measures should be designed into software of ECUs to provide reasonable operation in the event of a communications failure.

Electromagnetic Compatibility

Management of EMC is a necessary part of design of electronic systems. ISO 11783 based systems may add somewhat to the effort that must be made to manage EMC. ISO 11783 systems include a communications bus that conventional systems may not. On the other hand, dedicated wiring that might be used for communications in past systems is eliminated. Electromagnetic emissions and susceptibility of the communications bus of ISO 11783 systems have been studied extensively. Systems built to conform with ISO 11783 Part 2 have been demonstrated to meet current EMC requirements in the US and in Europe. Application of conventional EMC control practices as well as following the recommendations in the Part 2 document is likely to produce a system which will meet current EMC requirements. Testing to confirm the EMC performance of ISO 11783 systems is necessary.

Future

ISO 11783 forms a foundation for design of electronics in agricultural equipment in the near future as well as a foundation for its own extension and for development of future standards. The standard is designed to allow evolution and can serve long into the future. An initial set of messages has been created based on anticipated use of the standard. The total number of messages that can be defined in the standard is about 8500. Currently, less than 100 messages have been adopted or proposed. The process to create ISO 11783 has taken over seven years and evolution of the current standard may be the only way to allow the standards process to keep up with technological change.

The most critical factor in evolution of ISO 11783 will be customer needs. As customers demand improved performance, standards will evolve to support that demand. ISO 11783 now provides a flexible and expandable communication system to which modular components may be added. Standardization of network protocol has been heavily driven by cost lowering opportunities offered by allowing modular components from different OEMs to inter-operate on the same bus. In addition, standardization has been driven by the need for inter-operation of agricultural implements with tractor systems. Customer demand and inter-operability will continue to drive standard development in the future.

A significant physical constraint for evolution of the standard is the limitation on bus throughput. Opportunities to improve bus throughput are primarily constrained by the physical wiring and EMC constraints. ISO 11783 has been developed to comply with an OSI layered model. One of the objectives of that model is to allow the possibility that parts of the specification may be replaced without significant effects on the other layers. This is true to a large extent with the physical layer which defines the wiring system. If future technologies provide, for example, plastic optical fiber communication systems that are cost effective and serviceable, a new physical layer definition could be created and the standard could evolve to support it. The same possibilities exist for the other layers in the document.

An issue that constrains future evolution of the physical layer of the standard is that of the need to retain compatibility of connector systems at the hitch. Current tractors within the US use an SAE J560B connector at the hitch. As ISO 11783 systems evolve, we expect this connector to eventually be replaced by the ISO 11783 hitch connector. The Truck and Bus industry faces this same problem, and the industry has foregone including the SAE J1939 network on trailers in truck-trailer combinations at this point, because of the industry’s reluctance to change to a new connector. Serious efforts are underway in that industry to discover some way to carry a high speed network without changing the current connector. Agricultural equipment is posed to evolve to the use of a connector with network communications and will likely use that technology for many years.

The application layers of ISO 11783 define information and include the data dictionaries. In the future, it is likely that these portions of the document will grow to include additional information, but the current definitions will be retained and tend to influence network systems long into the future. The large undefined message space in ISO 11783 provides the opportunity for manufacturers to produce new applications of the network without significant constraints on the creation of standardized messages.

ISO 11783 has developed to allow support of precision farming systems. The standard has been described as a system to support precision farming. That perspective is a narrow view of the future opportunity to use the network to offer better products. The network can be used to allow tractor-implement coordination, and will allow improved interaction of operators with implements. The network can provide a component of the technology that will be needed in future systems to meet constraints imposed by environmental, energy, and economic concerns.

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