X-By-Wire via ISOBUS Communication Network

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ABSTRACT

Satellite based guidance technology is a very challenging principle for future automation of agricultural machinery. The first generation types of systems are primarily self-contained solutions and added to the existing system set-up of the tractor. As being an important step towards robotics in agricultural machines, a better integration of this technology into the mechanical, hydraulic and especially the electronic architecture is a major issue.

In principle, there are two main strategies for the integration. One is a concept based on a proprietary, manufacturer specific approach. The other one is to map as many functions as possible into the just state of the art becoming open and standardized ISOBUS. Within this paper, the capabilities of ISOBUS to be used for X-by-Wire applications are discussed from different point of views. In consequence, ISOBUS can only be used to create X-by-Wire applications with mechanical or hydraulic backup. Basic real-time capability with a reaction time of 100 ms seems to be achievable. However, some features of time-triggered protocols like determinism should be integrated by simulation on application layer level. Such concepts are the introduction of a heartbeat mechanism to serve as a coarse time synchronization and timeout reference. Additionally, the lack of unique and hard-wired addressing within ISOBUS demands new concepts like encryption algorithms.

Based upon these theoretical considerations, a first proposal for a Steer-by-Wire approach via ISOBUS has been derived and implemented. First results are very promising, but further investigations like fault injection trials and extended network set-ups with pre-defined bus load scenarios are necessary.

Keywords: Electronic communication, ECU, ISO 11783, ISOBUS, Steer-By-Wire, X-By-Wire

1. INTRODUCTION

The introduction of automatic guidance systems based on satellite navigation within the last few years was a great step towards robotics in agricultural tractors. This emphasizes the general trend of setting up systems, which allow more and more functions to be automated (Auernhammer, 2004; Reid, 2004). This comes, because electronic systems are able to do work better than the human driver. Important parameters are increased and stable accuracy at extended operational times. As the machines become larger for being more efficient, it gets even more important to have dependable and energy efficient systems which are able to operate in a harsh environment over leastwise 10 to 15 years.

A major prerequisite for the automation of functions is the interconnection of all basically self contained electronic systems in an agricultural working machine in order to realize a distributed electronic system (Munack and Speckmann, 2001). Since 1991, huge efforts of both industry and science have been undertaken on creating a standard for the interconnection of Electronic Control Units (ECU) in agricultural tractors and self propelled machines. Therefore, the ISO 11783 (ISOBUS) standard was formed (ISO, 1998). This standard defines an open communication protocol at physical and application layer level and is based on Controller Area Network (CAN) protocol (ISO, 2003).

The standardization of an overall agricultural communication system requires a very complex range of specifications. Major needs are supplying basic signals (e.g. speed, hitch position, ...) to implements, control of implements by a single user interface, automated data acquisition, task control, diagnostics, teleservice, on-line sensor technology, the integration of Tractor-Control-by-Implement scenarios and so forth. Today, the ISO 11783 standard comprises 13 parts with an overall size of several hundred pages. After publication of the Virtual Terminal (ISO 11783-6) in June 2004, various manufacturers have placed ISOBUS conform products on the market, and even more are expected in the near future. Therefore, agricultural equipment manufacturers have invested huge amounts of money for the development of this standard and even more for the design of compatible products. Currently, some manufacturers have set up their whole electronic product range upon ISOBUS. Accounting these facts, it can be assumed that ISOBUS will be the main communication protocol at least for the next few generations of agricultural machinery and equipment.

X-by-Wire is a concept, where safety critical operations of machines like steering, braking or power train control, normally done by mechanical or hydraulic components, are fully implemented by electronic systems. The communication network is therefore the backbone of X-by-Wire applications and has essential requirements like real-time performance, fault-tolerance, and high dependability. These requirements are mainly granted for time-triggered protocols (Kopetz, 1997).

2. OBJECTIVES

The main objectives of this paper are considerations about the integration of X-by-Wire functionality within ISOBUS networks based on CAN. A thorough analysis of the protocol, the interrelation of several parts of the standard and certain protocol mechanisms have to be evaluated in order to estimate the impacts on safety related issues. For that, basic principles and requirements of safe, fault-tolerant, real time communication systems need to be analyzed. At further, this should exemplary be pointed out on a real set-up of a Steer-by-Wire application.

3. STEERING AND NAVIGATION SYSTEM BASICS

For innovations based on electronic equipment, it is the normal case that these systems are self-contained solutions at first. In the second or third generation, these systems become more and more integrated within the overall system architecture. This can also be assumed for the whole range of automatic guidance systems for agricultural machines. Depending on the manufacturer (Noack, 2004), these systems typically consist of the following components:

- User interface,
- Navigation controller,

- On/off or proportional hydraulic valve as actuator,
- Real Time Kinematic Differential (RTK) GPS for high precision position information,
- Inertial Measurement Unit (IMU) for roll/pitch/yaw compensation,
- Steering angle sensor(s),
- Hydraulic pressure sensor(s),
- Activation/deactivation switch,
- Dead-man safety system.

Most of these components are added to the tractor with no or just partial interconnection to the major electronic architecture of the tractor (fig. 1). This first generation of Steer-by-Wire systems still remains with mechanical or hydraulic backup, acting as a redundant backslide layer (Pudszuhn, 2003). Due to IEC 61508 (IEC, 1998), those systems are categorized to Safety Integrity Level (SIL) 3 and need to be fail-operational, which means fault-tolerant by redundancy. A Failure Mode Effects Analysis (FMEA) (Martinus, 2005) of the hydraulic valve is therefore required. Additionally, the Steer-by-Wire mode is only allowed up to a maximum speed of 25 km/h. Although, these first generation X-by-Wire systems are fail-safe due to their intrinsic design, determinism of the message transfer, the service of a global network time, and redundancy at the timing services become already important (Führer et al., 2000).

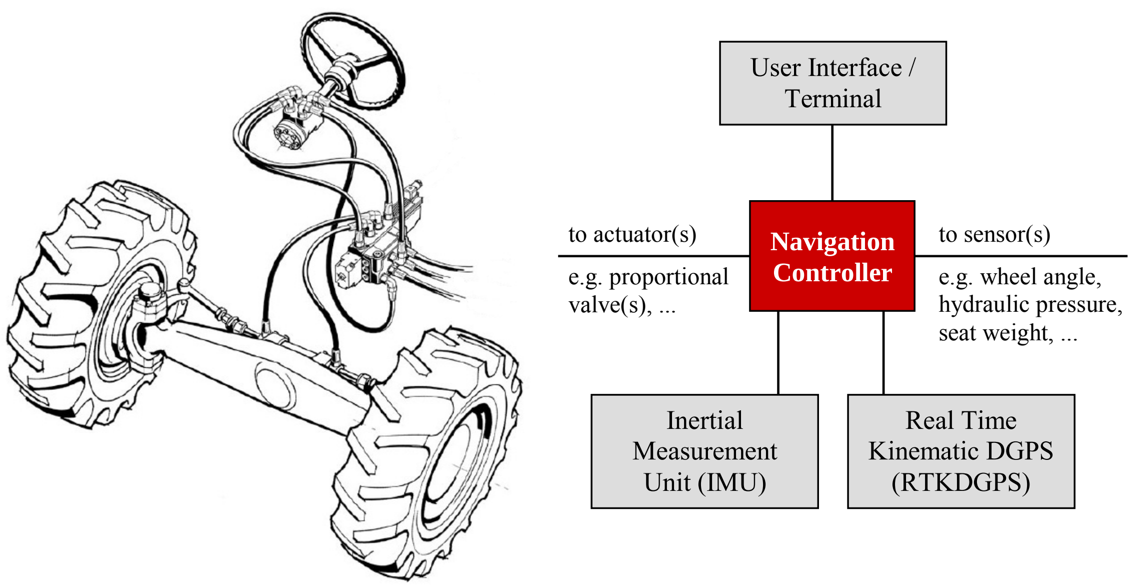

Figure 1. Typical system set-up of a first generation automatic guidance system for tractors.

Within the original hydraulic steering loop, an additional hydraulic valve with pressure sensors is fitted. Basic operation is to steer the system by steering wheel. The operator is allowed to assign the leadership to an electronic device such as a simple potentiometer, an electronic joystick or an automatic satellite navigation system. As soon as the operator touches the steering wheel which can be sensed by a pressure sensor, the leadership is automatically returned and the electronic input path is deactivated. This is very interesting for different working conditions in the field where the leadership of the steering wheel can be transferred to ergonomically enhanced devices such as a reverse driving facility.

The electronic steering path offers new strategies like the adjustment of

- the steering speed in dependence of driving speed,
- the maximum steering angle in dependence of driving speed,
- steering parameters due to tractor tilt (roll/pitch angle on hillsides).

In future, these systems need to be fully integrated within the overall electronic architecture of the tractor for offering new and optimized functionality. A deep integration of the navigation system allows not only to Steer-by-Wire, but also to additionally control Power-train-by-Wire like engine speed and the continuous variable gearbox in order to realize optimal strategies for regaining the parallel pathway after turning or the adaptation of driving speed because accuracy constraints can/cannot be met at lower/higher driving speed.

4. ARCHITECTURE FOR STEER-BY-WIRE INTEGRATION

To fully integrate an automatic navigation system within the electronic system architecture of a modern tractor with ISOBUS capability, there are basically two different strategies possible. The crux of the matter is the location of the navigation controller.

1. A tractor manufacturer with its own navigation controller (or having an exclusive agreement with an external company) has the ability to connect the navigation controller to the tractor internal bus segment. Here, the advantage is to have a much safer and predictable communication (for both event- or time-triggered protocols) as this segment has a known and fixed number of nodes after fabrication and therefore measurable delays and maximum bus loads under normal operation. This generally requires to implement the (often proprietary) tractor internal application-layer protocol within the navigation controller for acting as a proper network member. Also, there needs to be a user interface which might be an additional unit or requires a second communication channel to the external ISOBUS network for using the available VT.
2. From a third party manufacturer point of view, an integration is optimally realized within the external ISOBUS communication segment, where any communication is standardized and the VT can ideally be used as user interface. Here, the requirements on the communication safety and real-time needs are the crucial points to be considered. As shown in figure 2, the steering angle set-point has to travel thru the ISOBUS segment to the Tractor ECU, acting as a gateway to the tractor internal bus segment before arriving at the steering control ECU and being applied to the electro-hydraulic valve. Because of the gateway, a chaining of several hardly predictable delays is the consequence.

The first option is definitely the more safe way for integrating the navigation controller within the network architecture of a tractor, but has great drawbacks concerning flexibility and the realization of the user interface. Due to the actual ISO 11783 definitions, the tractor ECU has the only gateway functionality and not support transparent VT message transfer. If the communication protocol of the internal tractor bus is also based upon ISOBUS, a connection to a separate CAN channel of the VT can solve at least one problem. Considering ISOBUS as being an open, plug and play network for the interconnection of ECUs, the second option seems to be ideally suitable. As the number of nodes is not fixed and even runtime-extendable, the communication on this bus-segment is the unknown, unless there are mechanisms which guarantee safe and predictable real-time capabilities.

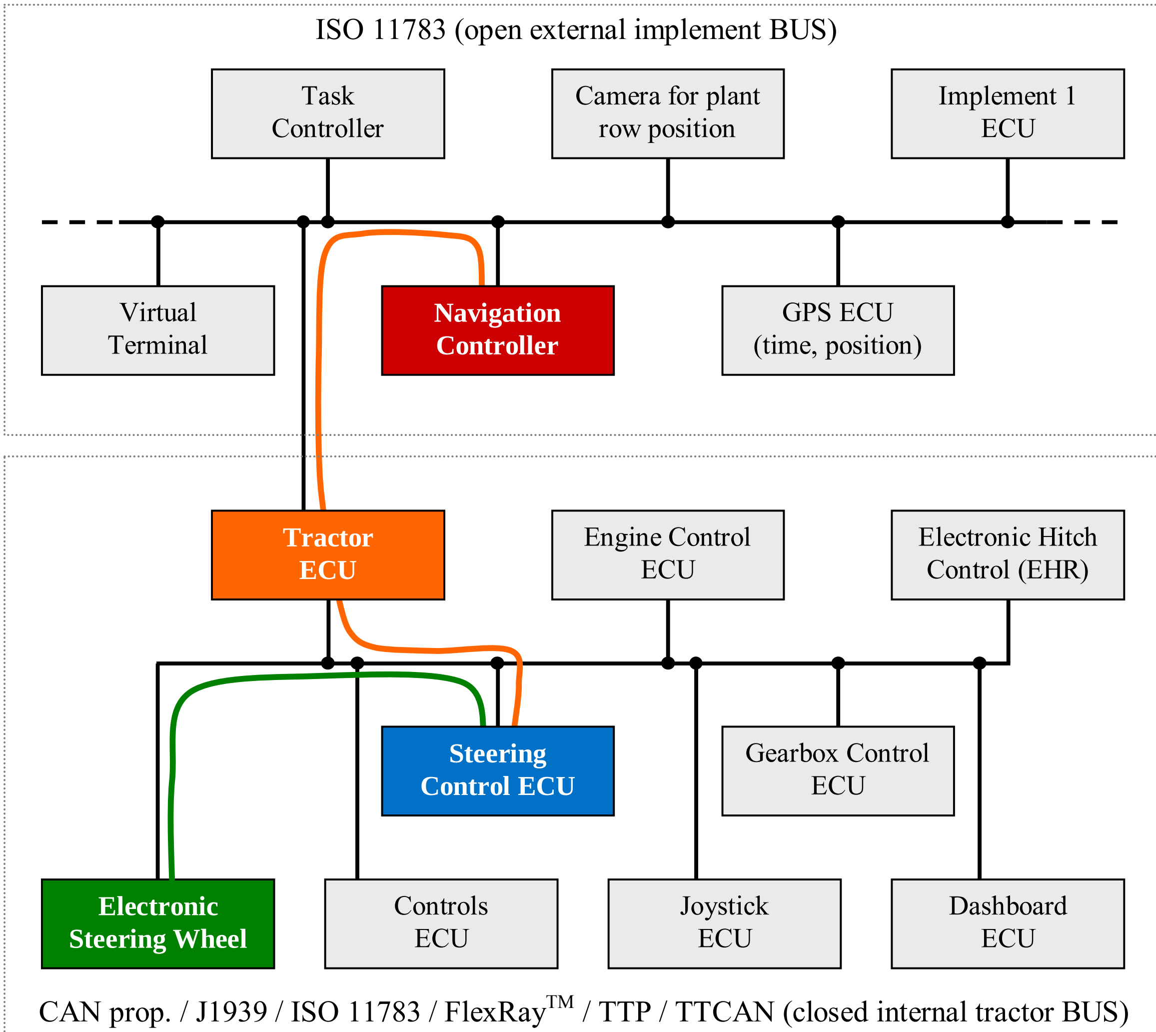

Figure 2. Network topology with navigation controller in external ISOBUS segment.

As automatic guidance systems are taking over the control of the steering functionality for a defined period of time, these systems can well be accounted as a Tractor-Control-By-Implement approach. Within ISOBUS, this concept is covered by Remote Control Messages (RCM) and was profoundly investigated by Freimann (2004). Another example for this approach is that an implement defines set-points for torque, engine speed or gearbox control which is generally a Power-train-by-Wire approach via ISOBUS. Here, the problems with delays and real-time requirements are of equal character.

5. X-BY-WIRE FUNDAMENTALS

X-by-Wire allows realizing and fully performing safety-critical operations of machines by electronic systems. Safe X-by-Wire applications are capable to meet many important parameters like fault tolerance, real-time performance, dependability, flexibility, scalability, and others (Kopetz, 1997; Kopetz, 1998). Within this context, several phrases and terms such as 'redundancy' or 'real-time' are often used and interpreted differently in literature. A comprehensive overview about these terms is given by Ehret (2003).

5.1 Redundancy

As ISOBUS is a very important standard for agricultural equipment, a weighty matter is to what extent ISOBUS can provide X-by-Wire functionality. Several publications already discussed the problems of CAN being used for those kinds of applications (Kopetz, 1998; Führer et al., 2000; Wei et al., 2005). Besides several issues, the main reason is the lack of redundancy of the physical communication layer (hardware redundancy). CAN does not allow to drive two replicated channels, because of the error detection and immediate retry mechanism. The deactivation of this functionality has already been considered, but therefore a very strong mechanism of CAN is lost.

The requirements towards redundancy of a system are depicted in figure 3. When a system is redundant, it is possible to detect and handle errors in some way. Redundancy can be divided in:

- Information redundancy: Such as checksums, acknowledgment, parity checks.
- Hardware redundancy: Replicated components, watchdog timers, and other hardware whose purpose is to increase dependability or to detect errors.
- Time redundancy: Such as double- and re-execution.

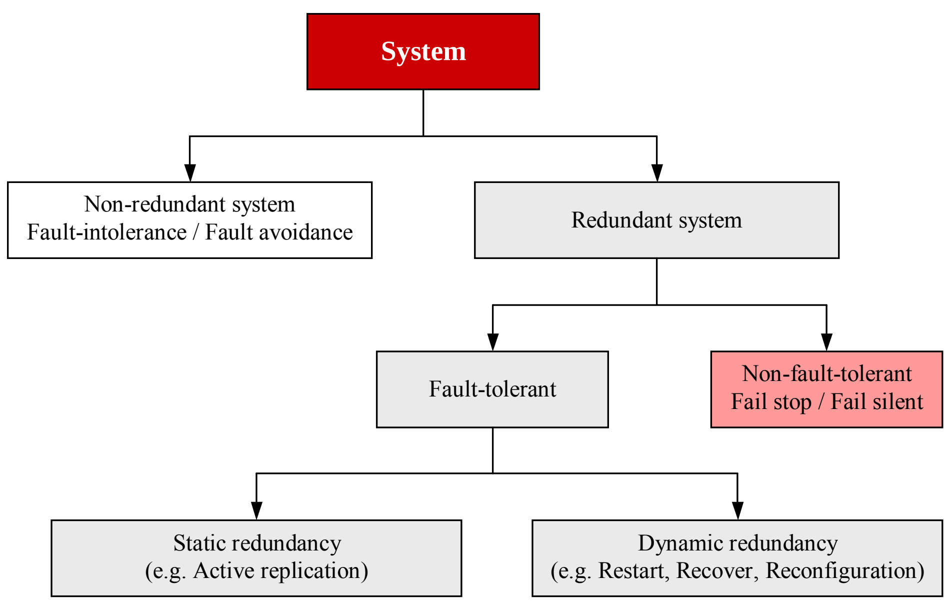

Figure 3. System redundancy due to Askerdal et al. (2000).

There has to be a clear distinction between X-by-Wire systems which have still a mechanical or hydraulic backup, as first generation guidance systems, and completely electronically controlled units being pure X-by-Wire systems.

5.2 Real-Time Performance / Capability

As real-time performance is claimed for X-by-Wire communication systems, this term needs to be clearly defined. An adequate definition can be found in the online encyclopedia Wikipedia.

In computer science, a real-time system has a time critical constraint i.e. operational deadlines from event to system response. Therefore, a non-real-time system is one for which there is no deadline. A real time system may be one, where its application can be considered to be mission critical like an Anti-lock Braking System (ABS). A distinction can be made between those systems which will suffer a critical failure if time constraints are violated (hard real-time), and those which will not (soft real-time). A system is said to be hard real-time, if the correctness of an operation depends not only upon the logical correctness of the operation but also upon the time at which it is performed. An operation performed after the deadline is, by definition, incorrect, and has no value.

For the definition of a control task, it is insufficient only to declare the task as real-time. The overall requirements are merely complete, after the time within the system has to react was defined. Due to the application, the value of this reaction time can vary within a broad range.

Picking up the example of navigation control of a tractor, the real-time reaction time is considered to be dependent of the driving speed. As faster the tractor drives, as shorter the reaction time needs to be. Actual systems usually calculate the position at 10 Hz interval, which is equal to the position output rate of the utilized RTKDGPS receivers. Furthermore, this type of Steer-by-Wire application is considered to be hard-real time. Also, Freimann (2004, p. 21) states that a cycle time of 100 ms for Tractor-Control-by-Implement approaches is sufficient.

5.3 Event-triggered versus Time-triggered

ISOBUS is based on CAN being an event-triggered protocol. This means, that a message is only sent when an event occurs. The arbitrating mechanism of CAN ensures that all messages are transferred according to the priority of their identifiers and the message with the highest priority will not be disturbed. This mechanism makes CAN very robust and provides high flexibility, but is not deterministic. The latency and jitter of a message with a certain priority at a certain time can not be guaranteed whilst dependent of the overall system condition. Even for a message with highest priority and thus always winning the arbitration process, the latency cannot be determined because of the error detection and immediate retry mechanism.

For pure X-by-Wire systems, the transmission of safety-critical messages must even be deterministic at the maximum busload. Hence, the concept of Time-Triggered Architecture (TTA) or hybrid protocols (time- and event-triggered) becomes essential. Currently, there are three different time-triggered protocols under discussion and development:

- Time-Triggered Protocol (TTP),
- Time-Triggered CAN (TTCAN), and
- FlexRay™.

Both, TTP and FleyRay™ are specified for having redundant communication channels and are therefore candidates for pure X-by-Wire applications. Wei et al. (2005) has compared these three protocols from an agricultural point of view and excluded TTCAN for X-by-Wire applications due to single channel design and therefore being non-fault-tolerant. Müller et al. (2002) has proposed mechanisms to synchronize TTCAN networks of any reasonable redundancy level which leads to fault-tolerant systems. Thus, all three types of time-triggered protocols still need to be considered for usage in future X-by-Wire applications in the agricultural area.

Particularly, the extensions of TTCAN (ISO, 2004) compared to CAN are of great interest, because the TTCAN protocol is realized in software in a higher layer on top of CAN. In TTCAN, all participants within the network are synchronized via the identifier of a reference message. As soon as the first bit of the frame, the Start of Frame (SOF) bit is recognized, the local time unit is synchronized and the individual participants know when to send their frames.

In TTP, the synchronization of all network members is done by a shared clock synchronization algorithm, which needs at least four nodes to work with the claimed precision. As true time-triggered systems are working with predefined time slots, the network design has to be defined and be common knowledge to all nodes before runtime. This makes TTA networks highly deterministic, but very inflexible concerning changes or extensions, because each node needs to be reconfigured. Another important property is the possibility to guard the bus against non authorized bus accesses by so called bus guardians. This allows the active prevention of the occurrence of Babbling Idiots on the network.

Comparing event- and time-triggered protocols, a broad range of different characteristics can be found. Table 1 shows a list of fundamental differences between both types of protocols.

5.4 Consequences for ISOBUS

Consequently, it can be stated, that ISOBUS only allows creating a fail stop/silent system (fig. 3, right) due to its CAN physical and data link layer. Therefore, ISOBUS can only be used to create X-by-Wire systems with mechanical or hydraulic backup.

Suppositional, using high prioritized messages and a precise timeout detection of the navigation controller, ISOBUS should be able to provide real-time capability with 100 ms reaction time.

Considering the comparison with time-triggered protocols, it can be assumed that deterministic behavior cannot be accomplished by CAN because of in-built error prevention. In order to minimize the delay, the Arbitration by Message Priority (AMP) mechanism can be utilized by using high priority identifiers for safety-critical messages like Steer-by-Wire commands. Another possibility to improve the timing behavior of the overall system and to allow remote detection of failures in other nodes is to implement heartbeat. This is a timed mechanism using coarse synchronization.

The problem that a bubbling idiot blocks the bus and thus prevents other nodes from sending cannot actively be eliminated in CAN networks. For a safety critical application, the only way to tackle this problem is to switch in fail silent mode and activate the redundant backslide layer.

Another safety-relevant issue emerges within the network management of ISOBUS. Each participant has to have an own and network wide unique source address, which forms the native addressing mechanism in CAN. The address must be claimed at startup due to a defined procedure and is afterwards used for the communication with all other nodes. Because the source address is assigned in a dynamic procedure and not hard-wired within the logic of each controller, it is very simple for any node to send messages with another source address. This type of error, whether intended or not can cause severe problems for safety critical applications. One way to handle this problem is that the real owner of a certain source address reacts when receiving a message of its own address. If there is no real owner, this is less critical but also needs to be prevented.

Table 1. Comparison of event-triggered (CAN) and time-triggered (TTP) protocols due to Kopetz (1998).

Characteristic	CAN	TTP
Application domain	Soft real-time systems with flexibility requirements	Hard real-time systems with composability, timeliness and dependability requirements
Temporal control	Event triggered	Time-triggered
Extensibility	Excellent in non time-critical applications	Only simple, if extension planned for in original design
Membership service	Not provided	Provided
Clock synchronization	Not provided	Provided in µs range
Replica determinism	Not provided	Provided
Latency jitter	Variable, load dependent	Constant
Media access	Carrier Sense Multiple Access with Arbitration by Message Priority (CSMA/AMP), collision avoidance	Time Division Multiple Access (TDMA)
Frame types	Data, Remote, Error, Overload	Initialization (I), Normal (N)
Error handling strategy	Immediate retry	Replicated channels, fail-silence
Load	Depends on number of events	Constant
Instant of sending	After event occurrence	Periodically, at a priori known points in time
Handling at receiver	queued and consumed on reading	new version replaces previous version, not consumed on reading
Consequences of message loss	Loss of state synchronization between sender and receiver	Unavailability of current state information for a sampling interval
Babbling idiot avoidance	No provisions	Independent bus guardian

6. TEST IMPLEMENTATION OF STEER-BY-WIRE VIA ISOBUS

On account of the mentioned considerations, a test implementation of a Steer-by-Wire application via ISOBUS was set-up and evaluated. In contrary to the formerly proposed integrated network architecture, all components of this test implementation were realized as ISOBUS conform devices. The schematic network structure is depicted in figure 4. The system was fitted to a FENDT Vario 818 which already provides full ISOBUS functionality by means of a Tractor ECU and a Virtual Terminal. The steering control ECU was designed as a closed loop control system by using a wheel angle sensor and a PVG32 proportional hydraulic valve of

SAUER DANFOSS as actuator. The steering controller provides VT functionality and can fully be operated via the FENDT Vario Terminal. Another ISOBUS conform controller, the electronic steering wheel also fitted with VT capability was designed and attached to the network. Here, a potentiometer is used to produce dynamic set-point alternations of the front axle steering angle.

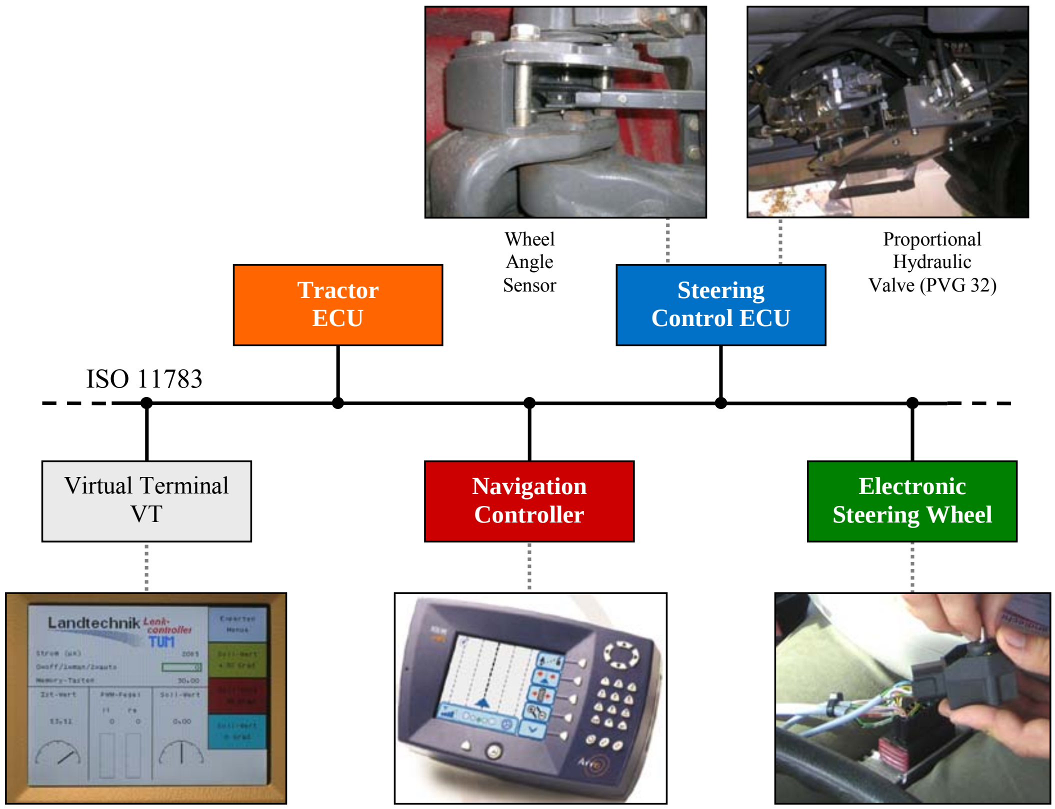

Figure 4. Schematic network structure of Steer-by-Wire application via ISOBUS.

As a first step, set-point changes of the steering angle have been applied via the user interface of the steering control ECU by simply pressing predefined buttons of the VT. Here, the communication messages are only of type ECU-to-VT and vice versa. The same approach is used for the control of implements like fertilizer distributor applications or others.

The first Steer-by-Wire relevant communication was achieved by sending changing wheel angle set-points by means of the electronic steering wheel. In order to address the formerly mentioned safety-related issues, a special communication mechanism was implemented. At first, a set-point sending routine of 10 Hz cycle time was established. In parallel, a special heartbeat mechanism among the steering control ECU and the electronic steering wheel was set-up at 5 Hz. This heartbeat mechanism serves on the one hand as a coarse synchronization and timeout mechanism, and ensures on the other, that both systems are vital and the sender surely uses its own source address. An encryption/decryption algorithm was applied on the values of the eight data bytes of each heartbeat message (DES, 1999). Alternatively, the ISOBUS NAME of both controllers was used for enhancing safety by means of the heartbeat message. After first feasibility tests, the system was comprehensive evaluated in field tests with up to 30 km/h driving speed. The system proved to stay fully operational without any interruptions under the given conditions. As ISOBUS is an open interconnection network, additional work needs to focus on the conduction of fault injection trials. The system needs to be stressed in a specific way to detect the critical points where the mechanical backslide layer becomes active.

As a second Steer-by-Wire approach via ISOBUS, the system was configured to accept and process steering angle set-points from the navigation controller of the BEELINE guidance system (fig. 4). In this case, it was not possible to introduce software changes on the navigation controller side, whereas the safety mechanism by heartbeat was deactivated. Again, the system was fully operational without any downtimes for a broad range of field tests.

7. CONCLUSIONS

With automatic guidance systems, a new category of automated functions of agricultural tractor and implement combinations emerges on the market, which needs to be considered especially from a safety-related point of view. In principle, there are two main strategies for the integration of these systems into the overall machine architecture. One is a concept based on a proprietary, manufacturer specific approach, based on the tractor internal bus. The other one is to map as many functions as possible into the just state of the art becoming open and standardized ISOBUS communication network.

Within this paper, the capabilities of ISOBUS to be used for X-by-Wire applications have been discussed from different point of views. In consequence ISOBUS can only be used to create X-by-Wire applications with mechanical or hydraulic backup. Under certain conditions, a real-time capability with a reaction time of 100 ms seems to be achievable. However, some features of time-triggered protocols like determinism must be simulated on application layer level by software. Such concepts are the introduction of a heartbeat mechanism to serve as a coarse time synchronization and timeout reference. Additionally, as there is a lack of unique and hard-wired addressing within ISOBUS, new concepts like encryption algorithms for cyclic keep alive messages are proposed.

By means of an exemplary implementation of a Steer-by-Wire architecture using ISOBUS, the above mentioned concepts have been realized and tested. First results are very promising, but further investigations are necessary. These are fault injection trials and extended network set-ups with pre-defined bus load scenarios. Future aim could be the establishment of a guideline for X-by-Wire implementations via the open standardized agricultural bus-system ISOBUS.

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