Mobile machinery communication concepts

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There is a growing demand for high bandwidth – not only for diagnostics, debugging, and operation/start-up, but also particularly for function control. This is not only about sensitive and safety-relevant data. It also includes visualization or camera data, which, due to the simplistic wiring of the system, is not sent through separate cables, but is rather transmitted through a central backbone of the vehicle communications system. In this article we present an overview of the current situation, a forecast of the communication requirements for the near future, and a specific approach for meeting these requirements.

Current situation

Typical system architectures in complex machinery are based on connecting several ECUs (electronic control unit) via a sufficiently robust and safe (or at least it is made safe with additional protocol stacks) communication channel. CAN is the best known such standard, including the CANopen and CANopen Safety protocol extensions.

This communications standard is perfectly adapted to frequent, fast, time-critical transmission of small data packets (data lengths up to 8 bytes, data rates up to 1 Mbit/s – possibly even higher with CAN FD). However, it was rapidly acknowledged that there is a need to transmit – possibly less frequently – larger data packets. This need is met by e.g. the CANopen standard, which allows for the transmission of data packets larger than 8 bytes. However, this affects efficiency: it operates by the de facto separation of a larger block into the aforementioned 8-byte low-level packets, creating payloads of only 4 bytes maximum per packet, i.e. a maximum efficiency of 50 %.

The problem of diagnostics and system parameterization can – at least ostensibly – be tackled at system level, envisaging a system with a central ECU with a suitably powerful interface (often Ethernet or USB; for the sake of completeness we should also mention EIA-232). There are obvious disadvantages to this: the central ECU must gather diagnostic data from the system in order to be able to provide information to the associated diagnostic tool. Meanwhile, configuration files go in the opposite direction: rapid transmission from the launch tool to the central ECUs, then painstaking distribution within the system to the relevant ECUs.

These disadvantages, as well as the limitations for diagnostics and parameterization, can be avoided by connecting one or more of the ECUs in the system to a suitable high-speed backbone. Standard Ethernet should not be the first choice here: it is clear that solely on the grounds of cabling and connector standards (as well as EMC robustness requirements), Ethernet is not a sufficiently robust standard for use in mobile machinery. By contrast, a standard like BroadR-Reach (already established in the automotive industry, it can be implemented with simple twisted-pair cabling and offers data rates of 100 Mbit/s) is ideally suited. This standard is also seeing increasing use in the field of off-highway machines, since as well as its technical characteristics, affordable components are available; the agricultural sector is leading this field.

Tomorrow’s requirements

As outlined above, a significant need will – we are inclined to think – continue to challenge generations of developers: the demand for sufficient bandwidth. It should be added that in this context, “sufficient” is a rather flexible concept (when does the memory of “640 KiB ought to be enough for anybody” fail to raise a smile?). The request for bandwidth can be outlined straightforwardly by dividing demand into the following categories:

Program downloads: Size of available program memory in ECUs is continually increasing, in line with ever-growing application complexity and thus application size. For interfaces that do not change, the time required to program an ECU thus increases correspondingly. This is a non-negligible
Debugging and testing: In the “good old days” developers were happy if they could view the value of an individual variable while the system was running, without having to pause operations. Now, as complexity increases, testing, launch, and debugging are shifting more towards high-level abstractions in the control system, meaning that rather than outputting individual variables, they aim to display the progression of numerical process variables over time. This is not only a challenge for the runtime system of an ECU; it is also a challenge to make available the necessary bandwidth for the transmission of all this information along with the process data itself. Furthermore, if a possibility of intervention in ECU behavior should arise (e.g. modifying parameters or variables at runtime), then functional safety during communications also becomes a relevant consideration – depending on the planned application area.

Visualization and display: As well as the increase in the quantity of information required for debugging and testing, there is an ever-widening array of displays for operating personnel, showing process, and system states throughout operation. Due to the requisite wide range of possible system configurations, the display device mounted on the operator’s platform does not always know all the details of some connected subsystem (e.g. a tractor-trailer with Isobus). The ECU for the attached unit (e.g. trailer) is responsible for providing the complete content of the operators display. It then becomes hardly surprising that the communication protocols currently used for this purpose – particularly subject to expectations shaped by mobile phone developments (“but..."
that's much clearer on my smartphone") – reach their limits relatively quickly.

Current communication approaches reach their limits even faster when the transmission of camera images (video streaming) also comes into play: greater bandwidth is needed to display areas not directly visible to the driver/operator (e.g. rear view camera, etc.) without making use of an additional network for transmitting analog video signals.

Given the current trend towards the Internet of Things (IoT), it can be assumed that Ethernet cameras will prevail over analog cameras. Particularly in the field of driver-assistance systems and self-driving machines, a significant share of the market will be given over to cameras with a direct connection to high-speed backbones.

**Process communication:** The requirements so far have been primarily concerned with use cases distinct from the actual control system operation, or with system status visualization tasks that are parallel to operation. However, the process communication itself also entails continually higher demands on communication bandwidth: increasingly powerful ECUs enable increasingly demanding processes to be dynamically controlled, thus making it possible to control systems which are not inherently stable in themselves and thereby improving their usability. As soon as the sensors, controllers, and actuators within a control loop of this kind cease to be connected to the same ECU, every communication between several ECUs gives rise to an unavoidable delay (or, in technical terms, time lag), which has significant consequences for the stability of the control loop.

For completeness, let us repeat here that the option mentioned initially, fitting out one of the ECUs with a suitably high-performance diagnostic interface, only meets one of the requirements mentioned in the above discussion, and that only partially.

**Cabling:** In addition to the performance specifications for communication channels, it should be borne in mind that the cost of an individual system cannot be arbitrarily increased to meet these. In fact, new technologies would ideally result in cost reductions. It can therefore be concluded that there should be as few connections as possible in the system (vehicle, vehicle - attachment or trailer, etc) – i.e., the cable lengths and the number of connectors should be minimized – and the requirements should be met using the most affordable media possible. To this end, a clear trend can be observed towards BroadR-Reach: an Ethernet-based standard which uses a simple twisted-pair cabling inside the vehicle.

**Implementation of requirements**

How would a future-oriented system architecture designed towards implementation of the above requirements look? For a simple system, the majority of the communications will be handled by currently commonplace standards (e.g. CAN or CANopen). A system is considered simple if it has the following characteristics:

- One central ECU in the system contains the complete control logic
- All other devices are smart sensors and/or I/O modules
- All process-relevant and diagnostic-relevant data is collected in the central ECU
- Only the central ECU has application-specific programming
- The central ECU is able to configure all other units (e.g. over CANopen)

With these restrictions, the need for a high-performance data connection within the system is reduced or eliminated. If the central ECU provides a dedicated diagnostic interface with correspondingly high bandwidth (e.g. Ethernet), then the currently foreseeable future requirements can also be handled well by a suitable system architecture.

However, the situation looks very different if this central role is not to be taken on by an individual ECU, but instead two or more ECUs form the intelligence of the whole system. The system architecture which then presents itself as suitable to meet the above requirements is a central communication backbone (e.g. based on the BroadR-Reach standard mentioned earlier). Technically, this backbone could be connected through a system diagnostic connector and also used for diagnostic purposes; however, it is recommended for security reasons that a gateway isolates the process communications from all externally accessible interfaces. This yields the additional advantage of being able to use an Ethernet connection as a diagnostic interface, thus...
eliminating the need for additional interface modules when connecting a laptop.

It also might make sense - depending on the system complexity - to provide for further gateways in the architecture at each location where simple systems (according to the above definition) could or should be amalgamated into subsystems.

A division into further subsystems can also significantly contribute to reducing the load on CAN networks, since CAN/Ethernet gateways (among others), are able to map CAN IDs to IP addresses. They can then transmit messages to targeted addresses in the required subsystems, minimizing the bus load in unrelated bus subsystems or segments.

Process data – integrity: At this juncture, it is worth noting that during system architecture development it must be constantly kept in mind that bandwidth is not the only concern: if a system – particularly a safety-relevant system – makes bandwidth available during operation for the above tasks, it must be guaranteed in all cases that there is never any risk of compromising data relevant to the core functioning of the system. The concept of Time-Sensitive Networking (TSN) emerges as particularly promising here: in a nutshell, TSN can be described as providing a way to define, at the lowest communication layer, channels that have different priorities:

- Time-triggered: These data channels can be statically configured to specify absolute times when the communication media should be reserved for them.
- Guaranteed bandwidth: The available bandwidth is guaranteed for these channels (comparable with a CANopen PDO which can be sent at a specified time, but does not have to be sent).
- Best effort: These are data channels where as much bandwidth can be used as is currently available (the currently possible best effort can vary over time, e.g. because a guaranteed bandwidth channel is not being fully used at a particular time).

Following the above theoretical treatment, we will now prove our solution, describing our demo system in detail. Effectively, the system is yet another inverted pendulum, but we have raised the bar somewhat beyond a simple implementation:

- The tilt sensor sends its values over CAN
- A gateway connects the tilt sensor with the backbone (BroadR-Reach)
- The ECU with control algorithm is also connected to the backbone
- The same backbone is used to transmit the video stream between the camera and display

Two of the data channels described above are used in this demo: guaranteed bandwidth to transfer control-relevant data values to the ECU and best effort for transmitting the streamed video image from the camera to the display.

The choice of an inverse pendulum for the demo system was based on the observation that relatively small delays in transmission result in the pendulum no longer being stable and calmly regulated, and it can be clearly seen starting to swing. The loss of values over even a brief time period leads to its complete collapse.

This is particularly clear when an adjustable noise generator (a source on the backbone which sends an adjustable number of data packets per second) is activated. The separate data channels achieve the desired result: no effect on the control values is evident, although it can be clearly seen that image transmission from the camera is visibly affected as the rate of noise packets increases, ultimately coming to a complete halt.

Summary

The pendulum demo described above clearly demonstrates how a combination of hard real-time requirements and maximum bandwidth usage can be achieved combining devices currently available on the market, such as the TTConnect 616, with technologies such as BroadR-Reach, to effectively and efficiently meet boundary conditions in off-highway system contexts. It goes without saying that the devices not only fulfill the relevant safety requirements, but also meet all other requirements for the off-highway sector – robustness, EMC, impermeability, vibrations, etc. TTControl has thus succeeded in taking an important step in the off-highway machinery sector, towards establishing high-performance networking technology for the industrial vehicle sector. These components make it possible for the manufacturer to implement up-to-date applications in their machinery; ideally, incorporated into existing system architectures.

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