# A "SMART SENSOR" BUS FOR DATA ACQUISITION

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## ABSTRACT

This paper discusses a "Smart Sensor" interface being developed for use in the Boeing Company. Several laboratory groups and Flight Test have joined in a study to define such an interface. It will allow a data acquisition system to record data from a large number of "Smart Sensors". A single pair of wires will form a bus to interface the sensors to the data system. Most systems will need more than one bus. Some needs exist for "Smart Actuators" as well to allow for closed loop control within the laboratories. The process control industry has developed several candidate busses. The groups are now in the process of evaluating the capabilities of the available busses to see which ones, if any, will do our job. To see if anyone else has similar needs, these requirements and the candidate busses are being shared. The goal is to see if some form of cooperation is possible.

## KEYWORDS

Data Acquisition, Fieldbus, Smart Sensor, Smart Actuator

## INTRODUCTION

During the development of the data acquisition system for the Boeing 777 we determined that we needed several new transducers. Some of the transducers selected were types with digital outputs. They had internal compensation to correct for the effects of temperature and non-linearity. Each type of transducer had a different output characteristic. What we needed was a standard interface between the transducers and the data acquisition system. However, at that point in time, there was not enough time to develop a standard interface so we found different ways to interface the transducers to the data system. After the 777 airplane data acquisition system was completed and testing was under way we decided to address the issue of defining a standard interface. This would allow the bus to be defined before we were under time pressure to meet an airplane development schedule. Several other testing organizations within

Boeing were contacted and most agreed that they had the same problem and that they could also benefit from such a standard interface. So several organizations put together a team to look into the requirements for such a standard. That team has completed the process of gathering the user requirements for the standard interface. The requirements have developed into the requirements for an interface that could be the basis for a distributed data acquisition system.

## GENERAL CONCEPT

One of the requirements that came to light early was the requirement to simplify the wiring as much as possible. The reason for this requirement is simply economics. It costs money to install a complex cable so the cabling should be as simple as possible. For airplane installations it is often necessary to cut access holes in the structure to be able to install a cable and to restore the structure after the test is completed. So the fewer cables needed and the smaller the better. In the laboratories the signal conditioning is often located in a control room which may be up to 1000 meters from the transducers. For a system with several hundred transducers, this translated into a lot of expensive cables. With this in mind, the concept that has been developed is for a single pair of wires that will carry power to the transducers and will return digital information to the data acquisition system for recording. The concept is not new, and is being used in several industries already. It is becoming common to find buildings wired this way. For example, the lighting will be controlled by signals transmitted over the power wires. This simplifies the wiring of the building and thus lowers the costs, if the electronics costs less than the wiring. So the general concept is for a system that will interconnect a number of transducers on a single pair of wires or bus.

## REASONS FOR CONSIDERING THIS APPROACH

There are many advantages to this approach over conventional approaches. A conventional approach would be to install a transducer in a remote location and run a cable to a centralized signal conditioner. The output of the signal conditioner would then be fed to a multiplexer that would drive an Analog-to-Digital converter. The output of the Analog-to-Digital Converter would then go to a computer or it would be output as a PCM bit stream to a recorder or telemetry system. The process involves running long cables from the transducer to the signal conditioner. These long cables are not only expensive to build and install but they create other problems. The excitation for the transducer needs to be precise since any variation in the excitation voltage will also show up in the output of the transducer. The voltage drop in the cables can be compensated for by running more wires but that just drives up the cost. The long cables also pick up noise that creates errors in the measurement. Until recently, the size and cost of the signal conditioning components have prohibited the installation of them within the transducer case or near the transducer. However, the modern integrated circuit and especially the Application Specific Integrated Circuit or ASIC has reduced the size and cost of these components. They are now small enough that we believe that it will be less costly to install the signal conditioning and the Analog-to-Digital Converter inside the transducer housing or very near the transducer itself. Having the signal conditioning inside the transducer will allow it to be optimized for the specific transducer. In addition, not having to run all of the long cables will make it feasible to measure not only the physical variable itself but other factors such as temperature or pressure that may cause errors in the measurement. The complex integrated circuits and microprocessors will allow the output from the transducer to be compensated for these other variables. Digital filtering can be applied to the output of the Analog-to-Digital Converter as well to remove any noise that may be in the measurement outside the band of interest. This all leads to a more accurate measurement for the same or less cost. The use of digital techniques and microprocessors will also allow the transducer to check its own operation in ways that are not possible with conventional techniques. However, the greatest advantages will only be achieved if we work together to define the interfaces to these devices so that the cost advantages can be realized.

## USE OF EXISTING TECHNOLOGY

One of the desires of the group is to try as much as possible to use existing technology where possible. We were aware that much work has been going on in other industries to develop similar concepts. The process control industry has been making an effort to develop the “Field Bus” for a number of years. This effort has yet to result in a unified US standard. However, the ProfiBus, which is being widely used in Europe, is an example of this technology that is available today. The automotive industry has adopted a system known as the Controller Area Network, or CAN, for use both in automobiles and in the factories. CAN was developed in Germany but is in wide use in the US as well as Europe. CEBus is being used in the building industry and others are known to exist as well. One of the goals of our effort is to try to determine which of these existing systems can be adopted as is or modified to meet our needs. In any case the first step was to determine just what the needs of the various laboratories and Flight Test were. From there we should be able to investigate the existing systems and then go from there. One effort that we found promising is the effort in the US by the IEEE and National Institute of Standards and Technology (NIST) to develop a standard definition of the elements that make up a “Smart Sensor” and the various device level interfaces. For the purposes of this paper a “Smart Sensor” is any sensor that produces a digital output. We have adopted a variation on the IEEE/NIST model for the transducers in our system. Figure 1 is the version of the IEEE/NIST Smart Sensor model that we developed in response to our customers inputs. The primary difference is the presence of an analog output that some users wanted for troubleshooting problems with the system. The use of actuators attached to what started out as a data acquisition tool is being considered by some of the laboratory organizations.

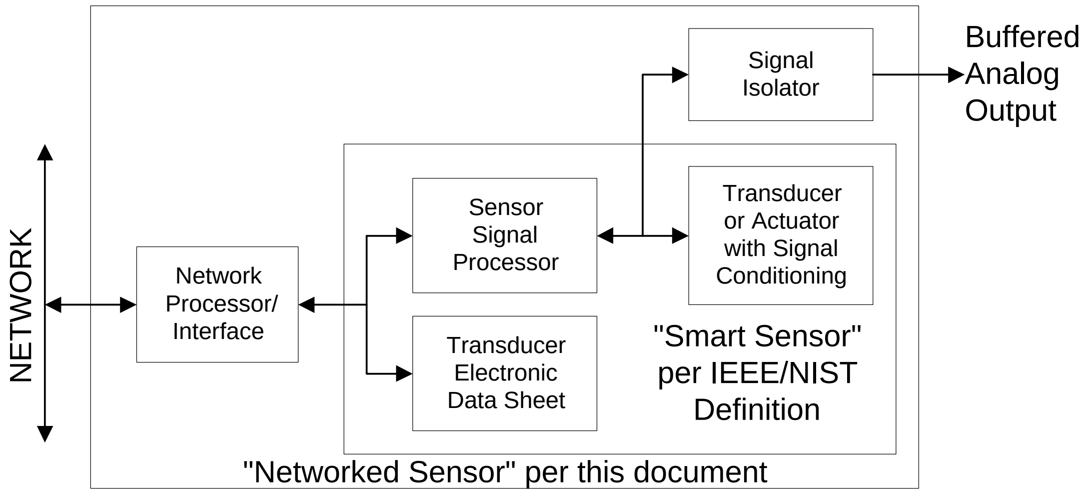


Figure 1 Networked Sensor Block Diagram

## SYSTEM CONCEPT

The general concept that has developed is shown in Figure 2. In this concept a number of busses would exist in the lab or on the airplane that would each connect a number of sensors or actuators to a central data acquisition and/or control system. The number of busses required and the number of sensors on each bus would be determined either by the physical addressing limits on the bus or by the total number of samples required from all of the transducers. Thus the bit rate of the bus will in many cases determine how many sensors can be connected to a particular bus. A number of these transducer buses can then be interconnected to form a complete system. For systems that are located within a small area the busses can be connected directly to the data acquisition system. If the system is spread out over a large area then the busses will be attached to a hub or hubs that will then be connected to the data acquisition system or control room via a high speed data link. The use of a hub allows each data bus to be less than one hundred meters long. The connection between the Hub and the Host Controller has not yet been investigated in great detail. This link may need to be up to one kilometer in length to meet the needs of some of the labs. A length of less than one hundred meters will meet the needs of systems on board the airplanes if a hub is required there at all.

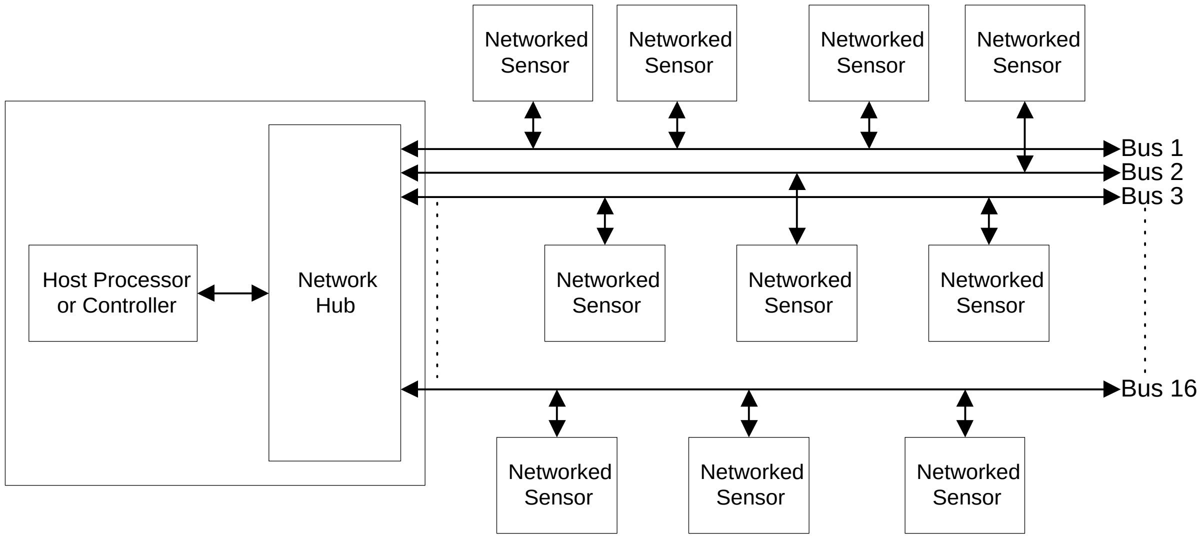


Figure 2 System Block Diagram

## DATA SAMPLING REQUIREMENTS

The requirement for a number of sensors to share a common data transfer medium requires that there be some method of sampling the data in the sensor and transmitting the data to the host when requested by the host or at the proper time within a sampling schedule. In order to keep the number of wires to a minimum the data transfer should be done serially over a single pair of wires. Again, in order to keep the number of wires to a minimum, the power for the sensors should be transmitted over this same pair of wires. The interval between samples of the output of a given sensor needs to be a fixed, repeatable interval in order for the data to be properly reconstructed during data processing. The user wants to be able to determine the order in which events occurred. This requires that the time between when the input of a given sensor is digitized by the sensor and when it is received by the host must be repeatable and known. These times need to be definable and repeatable within ±2 microseconds. In some cases the characteristics of the sensor will determine how well these two requirements can be met. For example a sensor measuring a frequency will need to acquire its samples at the zero crossings of the input waveform that will not be synchronized by the data system. These types of sensors will either need some time tagging capability or they will not be required to meet the ±2 microsecond requirement. There is also a requirement to define groups of transducers on a given bus that are sampled at the same time ±2 microseconds. These sensors will be sampled either on command from the host or at a particular time within the sampling schedule. The data would then be held in the sensor until it was time for it to be transmitted to the host. In order for the transducers to meet these timing requirements some form of common clock will need to be established for the system. This could take the form of the host commanding each sensor to sample it's data and when to return the data to the host. The other method that is being considered is to have the host provide periodic time commands and to allow each sensor to maintain the time interval between time commands. Requiring the system to operate in a command-response mode drives up the amount of traffic on the bus. However if each sensor maintains it's own clock, which is synchronized by the time commands from the host, more complexity is required in each sensor.

## DATA SAMPLING RATES

The laboratory and airplane data systems users requested that the system have the capacity to be able to support 12,800 samples per second for each bus. The users specifically ask that the number of bits in the output of a sensor not be limited to a fixed number. However, in order to be able to place bounds on the requirements for the bus, some number needs to be used. For purposes of determining the bit rate, we defined the number of bits per data sample to include sixteen data bits plus what ever overhead bits that the bus would require. This allows us to define the minimum bit rate requirement for the bus. The bit rate on the bus just to support the data transfer is only 204,800 bits per second. Adding in overhead, error correcting codes and dead time between transfers will increase the minimum bit rate. We expect it to be somewhere in the order of one million bits per second. The use of a command-response type of system would probably double this requirement. We still have the requirement for each sensor to be able to transmit more or less than sixteen bits and this will increase or decrease the number of sensors that can be supported by a given bus. The number of bits being output by each sensor will still have to be accounted for in the total number of bits per second. The sample rates for all of the networked sensors on a bus shall not necessarily be uniform. In other words, each sensor may have a different sample rate. This comes from the desire to run one pair of wires into a particular area, like an engine, and to be able to connect temperature sensors, pressure sensors and perhaps a vibration sensor to that pair of wires. If all of the sensors had to respond at the same rate the vibration sensor would drive the data rate and only two sensors would be able to share a pair of wires.

## PUTTING THE DATA INTO PACKETS

One of the things which can have a significant impact on the data rate that can be achieved is the overhead in the data transmission protocol. If a large number of bits are required to support the protocol compared to a few data bits this can limit the bit rate that can be achieved. The obvious answer to this problem is to collect the data samples into groups or packets. This will increase the number of data bits relative to the number of protocol bits and increase the effective bit rate that can be achieved. There are two areas where this is not acceptable. In the case of actuators with the sensor feeding data to the actuator over the bus. In this case the sample received by the actuator needs to indicate the output of the sensor at the time that it was received, not at some time in the past. The second area where this is not acceptable is in the current Flight Test Data System. This system has been designed to require that data be received by the real-time data monitor in the same order that it was acquired. With a packetized data system, this is not true. Packets containing data which is being sampled slowly will contain data that is much older than packets containing data which is being sampled at a higher rate. This is not to say that for other types of systems the technique of putting the data into packets may not be a useful way to increase the effective bit rate of the system, but it is not an answer for all systems.

## OPERATIONAL REQUIREMENTS

There are several operational requirements that have been placed on the bus and the sensors by the users. One thing that was universally requested was for each sensor to be able to identify itself to the host. Each sensor must also have the ability to run an internal diagnostic to determine it's own health. Other capabilities such as the ability to read and write the memories within the sensor over the bus were also requested in order to be able to setup the system. These requirements conflict with the controlled sample intervals and known time of the data samples described earlier. In order to meet both requirements two operating modes are being required for the bus. In the data acquisition mode all of the timing must be met and no unnecessary communications will be allowed. The setup mode will allow for all of the communications to be supported and for data to be acquired but without the requirements for the sample timing to be met. This is a natural way for the system to be used. During a test the system will be run in the data acquisition mode and nobody is allowed to request memory dumps or trying to setup a sensor during this time period. When a test is not in progress the system will be used to set up for the next test and for trouble shooting problems on the network. It is assumed that when the system is in the setup mode that the data acquisition schedule will be running in the background without the timing guarantees.

## FAILURES ON THE BUS

One of the users primary concerns about this type of system is what happens when a failure occurs on the bus or in one of the sensors on the bus. If the failure is of the type which allows the bus to keep running the diagnostic features of the sensors should allow the operator to quickly determine which sensor is bad and to take appropriate action. However, if the failure disables the bus the operator needs some way to locate the failure and take corrective action. Locating a failure when a number of devices are connected in parallel on the same bus is difficult at best but consideration of this problem will have to be made part of the bus design. Some things have already been identified and included in the requirements but the total problem will have to be defined when the system is designed. One common problem that could take the system down is a continuously transmitting sensor. To avoid this problem each sensor should have a detector built in which can detect this condition and shut the transmitter down. The most promising approach for finding shorts and opens on the bus may be related to the physical bus topology. A topology or implementation needs to be found which will allow parts of the bus to be quickly isolated for troubleshooting purposes. Even this may be difficult if the bus is buried within the wing of the airplane. The use of error correcting codes and other techniques to make the bus more robust will help but the solution will have to be determined when the technology is selected.

## CHANGING A SENSOR

Since we envision a bus which is running it's data acquisition schedule any time it is powered up, unless specifically shut down by the operator, what happens when a sensor is added or removed from a bus. Again some of these things cannot be fully defined yet but the general concepts can be discussed. The first assumption is that these things only occur when the bus is in the setup mode. If a sensor is removed from the bus when the bus is operating its data will simply not appear in the host. The system should have a way of detecting this event but what happens after that is not yet defined. If a sensor is added to the bus it should not start transmitting its data until it is integrated into the systems sampling schedule. This conflicts with the idea that it should come up running when it is powered up, so some interaction with the host will probably be required after power up before any sensor starts transmitting data. Another requirement is that the addition or removal of a sensor from an active bus shall not cause more than a momentary interruption of the operation of the bus. For example if a transmission is in progress when a sensor is connected that transmission may be corrupted. That is acceptable. However, after the transient on the bus is gone the bus must continue in normal operation without any operator action. It is not acceptable to have to reset the bus or system to recover from this type of event.

## PHYSICAL REQUIREMENTS

There are many physical requirements that must be addressed during the development of the system. The bus may be required to operate out-of-doors in some of the labs. This will require that the bus be able to withstand rain, heat, mud and many other environmental conditions. On the airplane many of the same requirements must be met. In addition vibration and even greater temperature extremes are normal. The system will be required to meet stringent EMI/RFI requirements before it can be installed in the airplane. The exact environmental specifications have not been defined. We know what the requirements are but we would prefer to use a generally available standard to make it easier for vendors to qualify parts without working directly with us at least in the beginning of a sensor development. It is also felt that a recognized standard would be more easily understood by outside vendors. In some cases, the environmental requirements will be so specific for a given sensor that a general specification will not be useful. However, we hope that this is the exception and not the rule.

## ANALYSIS OF EXISTING TECHNOLOGY

At the time of writing this paper we are in the process of evaluating the available busses. It is relatively easy to eliminate some of these busses. CEBus and LONWorks appear to be to slow to support the data rates that are desired. CAN is marginal. It can support the data rates but not with the desired cable lengths. It would also require the use of a four wire cable. CAN has a very desirable attribute in the wide availability of integrated circuits which support it. Perhaps with some modifications of our system concept CAN could be used. In the US Fieldbus Foundation has joined forces with World FIP to complete the work started by ISA. To date this effort has resulted in the definition of the physical layers of a fieldbus which is covered by the ISA Standard S-50 part 2. This total capabilities of this bus cannot be determined since the higher protocol layers have a significant effect on the data sampling rate. The only other Fieldbus being considered is ProfiBus. ProfiBus has several different speed ranges. The ProfiBus-DP runs at rates up to 12.5 Mbits per second which would appear to be fast enough to meet all of our requirements. The available literature indicates that with thirty-two sensors on a bus, each making 512 bit transfers each transducer can be sampled 500 times per second. This gives a total sample rate of 16,000 samples per second. ProfiBus-DP is a four wire bus instead of a two wire bus but this may be acceptable or we may be able to adapt it to a two wire bus. There is still quite a bit of work to be done to determine which bus to use and how to implement it but it seems to be very possible to accomplish most of our goals.

## SUMMARY

The Laboratory Groups within the Boeing Commercial Airplane Company have started a project that we expect to lead us to a standard way to incorporate “Smart Sensors” into our future systems. We have talked to a number of other groups within Boeing and they are following our development with the hope of being able to use what we develop. At this time we are making our requirements and findings available to other organizations in the hope that two things will happen. One, we would like to receive input from other organizations that have similar jobs to do. If there are requirements that we can incorporate into our documents that would make the final product more useful to other organizations then we would like to incorporate them. If this happens we would hope that other organizations would adopt the same system making the technology more widely available. This would lead to the second thing that we would like to see, lower cost. The more people using a technology the less it would cost each individual user.

## ACKNOWLEDGMENTS

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