Distributed Industrial Sensors Systems (DISS's) using the BBB

Does it Make Sense?

Small computer boards have become very popular recently among hobbyists and makers; examples of these boards include: the Arduino, the Raspberry Pi, and the Beaglebone Black (or BBB) (http://www.technologyreview.com/view/514036/beaglebone-black-a-makers-dream/). These boards are small, inexpensive ($35-$45), but still very powerful. There are numerous examples easily found where these boards have been connected to a wide variety of sensors to realize sophisticated systems. (in Google Search type: youtube beaglebone black). Can these boards be effectively used to realize Distributed Intelligence Sensor Systems (DISS's) in industrial applications? To help answer this question, two reference designs have been developed: the first design allows the BBB to be connected to four different sensors having digital interfaces; the second reference design converts a traditional industrial Wheatstone bridge sensor to have a digital output. This article describes our experiences in developing these reference designs intended to be used with the BBB, describes the capabilities of this approach, and also gives a number of recommendations for others considering using a similar approach.

Advantages

Using DISS's for industrial automation offer advantages of secure encrypted communications and data transfer to a central and/or remote monitoring system. DISS's continuously check their status and health; this often includes power-supply voltages, temperature, and connectivity to the sensor and to the central monitor. Faults are immediately detected, the central monitor is informed, alarms are triggered, alarm e-mails are sent, and corrective action is quickly initiated to minimize plant down-time. Other advantages include both distributed and central data logging, and digital communication links that are much less susceptible to electromagnetic interference and noise. Historically, DISS's were prohibitively expensive; recently the hardware costs have plummeted to be only a minor factor. For these reasons, new factories are being designed with DISS's in place, and older legacy plants are being upgraded.

Risks

However, changing to a DISS-based plant is not without risk; a DISS is significantly more complex than a legacy analog-based sensor system. The distributed intelligent nodes are “full-fledged” computers, and unless properly set-up and maintained, the added complexity can potentially become a “show stopper”. If improperly designed, the system may never work, and plant operation will be at risk. Choices are: 1) keep the traditional, analog-output, non-networked, sensor system; 2) use a system from a large established sensor company (such as GE Measurement and Control, Rockwell Automation, Siemens, or STMicroelectronics, as examples); or 3) install a new-generation DISS-based approach. Alternative 1) may eventually leave the company non-competitive. Alternative 2) is a viable interim approach; however, it has disadvantages that systems and maintenance can be very expensive, proprietary, and don't take advantage of most of the recent game-changing advances. Alternative 3), which this paper focuses on, offers many advantages, but users must be prepared for on-going custom development requirements, and do not want to embark on such a development unless they are

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prepared to do it right.

**Required Expertises**

Designing DISS's into industrial plants requires a wide variety of expertises; these include analog circuit design, digital circuit design, computer programming, operating-system maintenance, GUI programming, secure encrypted Internet communication protocols, etc. Few service houses have capabilities in all of these expertises. When deciding on whether to install or convert to a DISS approach, a critical question is whether the necessary expertise is available, whether from in-house engineers, or from the selected design-services company, or from both? Does the business model support a *working together* approach to get the job done?

**Re-Inventing the Wheel**

Another important question is do critical sensors and interfaces need to be designed from scratch, or can they be realized by modifying existing designs. In some cases, reference designs can be customized to meet customer needs with only minor fast turn-around changes; in these cases, custom designs can possibly be developed in only a few weeks. Many, if not most, industrial sensor systems are highly custom; by basing a solution on a generic pre-developed reference design, risk and development time are minimized, while still meeting the customer's custom needs. In addition, the features of the reference designs are evidence of capabilities, and allow customers to more easily assess the value of investing in a DISS approach.
One of our first reference designs is the development of a ‘Cape Board’ that is intended to be used with a BeagleBone Black intelligent node. The Cape is shown in Fig. 1. Very similar interface boards can also be used for other small-board computers such as the Arduino and the Raspberry Pi. This Cape allows an inexpensive ($45) BBB computer to be used to interface to 4 independent digital output I^2C serial buses where each bus can be connected to one or more sensors. The I^2C serial bus is one of the most popular standards for interfacing to digital output sensors and is quickly gaining in popularity (for example, see: http://sensing.honeywell.com). The Cape can be modified for other industrial digital sensor interfaces such as the Modbus, Profibus, other Fieldbus standards, or the CAN Bus. The board includes 8 General Purpose Input/Output connections (GPIO's) which can drive relays or sense external digital signals, monitors its own power-supply voltage and temperature, and has a programmable output voltage to support both 3.3V and 5V applications. It also includes an EEPROM for additional data logging and to give it “Black-Box” functionality.

A second reference design, also shown in Fig. 1 (the small round board), is used to convert traditional analog sensors to digital interface sensors; it is placed between a Wheatstone-bridge based sensor, and conditions the small sensor signal by amplifying it, eliminating offsets and non-linearities.
with very high accuracy, and converting the conditioned signal to a digital output again based on the
\( \text{I}^2\text{C} \) standard. This reference board is intended to be encapsulated directly into the sensor. The sensor
conditioner supports digital calibration of gain, offset, and non-linearity, that can all be dependent on the
\textit{temperature at the sensor}; we have extended this calibration approach to support both calibration
at the time of manufacture and updating/adapting the calibration coefficients in the field during actual
operation. An example of where this is desirable might be in measuring gas or liquid pressures, where
the media being measured is changed, and it is desired to cover a different pressure range. It also allows
a single product to be used in a wide variety of different applications minimizing inventory costs and
complications. Having a digital interface allows for all connections right up to the Wheatstone-bridge
being continuously monitored. In addition, sensor interface power-supply voltage, Wheatstone-bridge
excitation voltage, and temperature can all be read, to ensure system integrity, and logged by the BBB
computer board, and also continuously communicated to the central monitor, and logged there as well.
If any component or communication link is lost, the data is still preserved as it is saved in non-volatile
memory. With the distributed intelligence, sensor operation continues even if the Internet link comes
down. When there is a problem right at the sensor, the fault is detected, and the alarm is immediately
communicated to “head-office” and can optionally be e-mailed or texted directly to maintenance
personnel.

\textbf{Minimizing Costs}

The hardware cost of retrofitting a legacy plant to a modern digital sensor solution is very close to
actual component costs, and \textit{this cost is minimal}. Labor costs are minimized by basing custom designs
on pre-developed reference designs. The customer pays for the time necessary for the customization
necessary to meet their particular needs, for the time required for installation, and for desired
maintenance; the customer does not pay for the previously-incurred development costs of producing
the reference designs. Software costs are minimized by initially installing a simple system to match
current capabilities, and then upgrading the system on a need-to-have basis as the needs become more
apparent. Also, by using a mature operating system for the BBB, such as Ubuntu, Debian, or Android, a
wealth of existing software packages are available which greatly minimizes the amount of new
software development necessary.

\textbf{Networking}

The current reference designs enable connecting \( \text{I}^2\text{C} \) sensors to BBB computer boards which are
then networked using secure SSL encrypted communications over the ubiquitous 100Mbs ethernet
standard. The ethernet links can be standard twisted pair (CAT-5e or 6), although shielded twisted-pair
(CAT-6a or 7) is recommended for better electro-magnetic interference (EMI) rejection. Other
alternatives are Power-Over-Ethernet (POE) cables and optical cables. Optical cables are highly
recommended for harsh environments with large EMI; Plastic Optical Fiber (POF) connections are
often preferred because of their low price, extended reach, small bending radii, \textit{light weight}, and
especially due to their \textit{ease of installation}; they can be quickly cut, terminated and installed in the
field; this significantly simplifies difficulties and costs of upgrading legacy plants leap-frogging
competitors using alternative approaches.
Board Comparison and Limitations

Our experiences in exercising the reference designs were: 1) the BBB board is robust and well-designed. It’s additional capabilities are well worth the additional $10 cost compared to the Raspberry Pi; the most valuable extended capabilities include: ability to run a much larger operating system from the SD card; much larger RAM, greatly expanded I/O capability, especially when interfaced through the “real-time” 32-bit PRU co-processors, and higher speeds. Also, the BBB runs much cooler than than the Raspberry Pi which simplifies putting it in an enclosure and could improve long-term reliability. The major limitation regarding the board (in our opinion) is the lack of a real-time clock chip; we intend to include one on the next version of our cape. Also, we are guessing that the real-time PRU’s included in the Texas Instruments AM3359 chip were originally intended primarily to get data to and from a core DSP chip; replacing one of the two PRU’s by a DSP core, even a simple one, would be a substantial improvement (TI, are you listening?). Doing real-time signal processing using the PRU’s, although possible, is exceedingly difficult (i.e. takes a lot of assembly instructions for operations that should be done in one step) due to the limited set of arithmetic op codes. This is a non-issue for accessing the reference designs for most industrial applications, but could be an issue in future applications.

Software Issues

The major difficulty in using the BBB to interface to our cape and sensor chip were due to software complexities coupled with poor documentation. The Angstrom operating system, that ships with the BBB, was chosen by the BBB manufacturer (http://circuitco.com) because it is light-weight and requires a relatively small amount of non-volatile storage (the BBB comes with 2Gbyte eMMC chip); plus, it boots up fast, and is easily to access for new users. This operating system has a number of differences from more standard Linuxes that caused difficulties, and that coupled with poor documentation, were hard to surmount. Examples include a non-standard SSL implementation, and the use of conman for networking; both of these are problematic. Other choices for OS’s are: Debian and Ubuntu (which is based on and similar to Debian). Support and documentation for all choices is lacking; as is Texas Instrument's support for the BBB, especially for BBB software. The most significant support for the Beaglebone Black is the excellent work of Robert C. Nelson (https://plus.google.com/106813818225399872098/about) who is primarily responsible for most working OS kernel images running on the BBB. After a number of hard-to-solve problems using Angstrom; we moved to Ubuntu which in our opinions was superior (and used more standard approaches). Ubuntu is supplied by Canonical, but their support for the BBB is lacking, and there are reports that Ubuntu includes “spy-ware” which is problematic in secure industrial systems, unless disabled; and can one ever be sure it is completely disabled? We intend to move to Debian in the near future for this reason (and also due to the lack of support from Canonical). Currently, using Android on the BBB is problematic because support of it (on the BBB) is very lacking, and most current versions are based on the Linux 3.2 kernel, rather than the 3.8 kernel which has device tree support (mandated by Linus Torvalds – the father of Linux) for accessing device drivers. This situation is changing, and using Android on the BBB will be an option shortly, but may be experimental for some time. There is no good documentation available for properly explaining the use of device trees on the BBB (most documentation was written in the days of the PowerPC), although there are numerous examples that can be used as starting points.
Conclusion

Despite the problems, we have been successful in working though practically all the software issues, but this took considerable time, and is a moving target as the OS's are being continually upgraded and to date do not include long-term stable versions. We expect this situation to improve as time goes on. Our recommendations is to get to a good working image, and then stick with it until the time of the next major upgrade, which should be well tested prior installation. We also recommend that a company planning on using the BBB for industrial applications work with a Service Provider that has already worked through most of the issues. Alternatively, one could use the much better supported and documented, but less powerful and high-temperature Raspberry Pi; we have worked through the issues with the BBB and recommend it as the preferred choice.

In summary, the advantages of converting to a digital DISS approach are many, the risks are also many and must be managed; this is best done by relying on proven excellence.

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Cape Board Features:

- 4 individually addressable I²C outputs; each output can connect to multiple I²C slaves
- 8 GPIO digital signals; each signal can be programmed as input or output; each signal can be individually read or written, or all 8 can be read or written simultaneously (even with mixed input and outputs)
- Digital Interface voltage can be programmed between 3.3V and 5.0V
- Interface voltage can be continuously monitored
- Cape temperature can be continuously monitored
- Cape has EEPROM for non-volatile data logging; allows for “Black Box” functionality
- Cape interfaces to BBB which appears as a “node” on local internet, and includes SSL server for encrypted communications, firewall, privileged user only access, etc.

Sensor Interface Features:

- Connects directly to Wheatstone-bridge, no other electronics required
- Highly accurate and linear with very low noise
- Is digitally programmable to accommodate a wide range of gains, and offsets; one design is widely applicable to many applications minimizing inventory costs
- Has calibration for gain, offset, and sensor non-linearity
- Calibration is stored in non-volatile memory
- Calibration is temperature dependent
- Calibration can be changed or adapted in the field during operation; allows for sophisticated adaptive control feedback loops
- Power-supply voltage, Wheatstone-bridge excitation voltage, sensor-interface temperature, and connections right to Wheatstone-bridge are continuously monitored to allow for instantaneous fault detection.