AC 2008-1511: HOW MANY ENGINEERS DOES IT TAKE TO MAKE A MEASUREMENT?

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Abstract

The emergence of nano-technology has driven the evolution of instrumentation tools and has revolutionized the measurement industry. The new technology also impacts engineering education with challenges to prepare the next generation of graduates to be competent and effective in this rapidly evolving field. This paper examines three current industry applications and explores their implications for curriculum development and delivery. The first application involves measuring the performance of prototypes to validate automobile design. The second concerns continuous status assessment of missiles and the third deals with instrumentation embedded within advanced production tools used in the semiconductor industry. Inexpensive embedded instrumentation empowers data generation requiring a fraction of the human resources and at an acquisition rate many orders of magnitude greater than was possible even a decade ago. The new measurement technology puts emphasis on timing, accuracy and stability, troubleshooting and formatting gigabytes (and more) in a reliable and unambiguous way. The paper offers an example showing how these changes can be incorporated into a typical curriculum without massive restructuring.

Maintaining educational relevance

Every technology-focused educational group goes to great lengths to maintain the currency and relevance of its programs. The most common methods are:

- Receive advice from an Industry Advisory Board. The process works well, especially if meetings are held more than once per semester and the industry members carry their message into the class-room as guest speakers and act as hosts for company visits.
- Through conferences, research and applications-focused partnerships. Opportunities for hands-on experience and student involvement through internships and projects follow.
- Provide a series of short courses for industry. The issues are always pragmatic and often very basic but there is no better way to learn about the practical skills requirements in the workforce. The success criteria are harsh. If a course does not add value, it will not survive no matter how enthusiastic its academic proponents may be.

The authors use all three methods of interaction. One conclusion is that the world of measurement is changing rapidly. It would be easy to miss this outcome since it is not unique to any particular course or technology. However, it touches on every aspect of product design, manufacturing and support so the implications are important.

To determine the scope and nature of the changes and trends in industry practice, a number of case studies were undertaken. They are drawn from the activities of a combined industry-academic team that oversees the scope, content and outcomes of a series of industry short courses on instrumentation [1]. The purpose of this paper is to present the outcomes of three use-cases, to infer skills and techniques that need further development and to show how the conclusions are being used to shape the content and priorities of a degree program.

To answer the question posed in the title of the paper, measurement productivity has increased by many orders of magnitude over the past two decades. The effort to make a measurement can now be assessed in units of “nano-engineers”. There have been few dramatic breakthroughs but each new system generation incorporates more automated measurement and control features so that over a period of years the generic principles have been extended into totally new applications contexts. However, they may be most simply summarized as a natural consequence of the increasing complexity and requirements of electronic systems. The paper offers a snapshot of three typical industry trends and an academic response.

Use case 1 – Automotive.

The achievement of greater economy, reliability and safety in cars relies heavily on greater use of electronics to measure a wider range of functions and thus allow more sophisticated control and diagnostic algorithms to be implemented. Some are controversial such as the use of ‘black box’ data for accident analysis [2]. However, there is also a more general question; how does the data from a real event like that shown in Figure 1 compare with the evaluations from controlled crash tests?

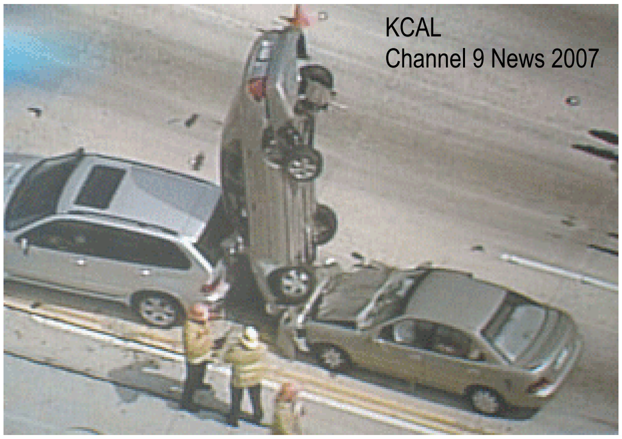

Figure 1. Reality can be different from lab conditions

This is an example of a general and rapidly developing instrumentation requirement. Almost all product design makes heavy use of simulation. This approach has given massive performance and quality improvements but the simulations still have to be validated, especially under worst-case conditions. A good example concerns under-hood temperatures. A casual inspection of any modern vehicle is enough to show that there is very little space available under the hood and temperatures can often rise to 150 ^{o}C. Since reliability decreases rapidly as temperatures rise, it is important to have values for under-hood temperatures. Simulation of thermal sources and air-flow can give reasonable predictions. However, towing trailers up long grades with an ambient temperature above 40 ^{o}C provides a severe test of both engine cooling and air conditioner performance. For these reasons, all the major automobile manufacturers have hot-weather proving grounds for extreme climate testing. To test the real temperature distribution, vehicles are typically instrumented with hundreds of thermocouples to measure both under-hood and interior temperatures. The vehicle is then run for many hours under extreme conditions while recording temperature as well as an extended range of performance details to determine whether there are any operational conditions that exceed the design limits or invalidate the simulations.

Use case 2 – Missile readiness

Military equipment also faces severe environmental conditions. However, it has additional requirements that demand a different approach to guarantee effectiveness. A good example is an air-to-air missile as shown in Figure 2.

Figure 2. Air-to-air missile

The missile will only be used once but it may have a twenty year life. In the waiting period, its location and status have to be known at all times. The missile may also be stored and handled under non-ideal conditions. On an aircraft, it may be on the ground on a desert airfield or in icy salt spray on an aircraft carrier. It can be rapidly taken to – 50 C at altitude and then back to ground. This cycling process through extremes of temperature and vibration goes on for years until just once, the missile has to do its job.

The requirement is to collect information that will confirm that the missile is always fully operational when deployed. Under factory test conditions, this is reasonable but in the field, there are extremes of environment, the time intervals between data downloads are uncertain, many different crews will be involved and over the decades of deployment, the technology involved in all aspects of test and control will change substantially. The stakes are high; in modern warfare, there are no second shots.

Use case 3 - Manufacturing

High-tech manufacturing is invariably capital intensive. Nowhere is this more evident than for integrated circuit fabrication. A state-of-the-art semiconductor plant costs about

$4 B. It contains more than a thousand tools that run continuously but it still takes several weeks for a silicon wafer to go through its complete fabrication cycle. Although there are dozens of different tool types that perform functions as varied as ion implantation, optical imaging and plasma etching, they all have the generic structure shown in Figure 3.

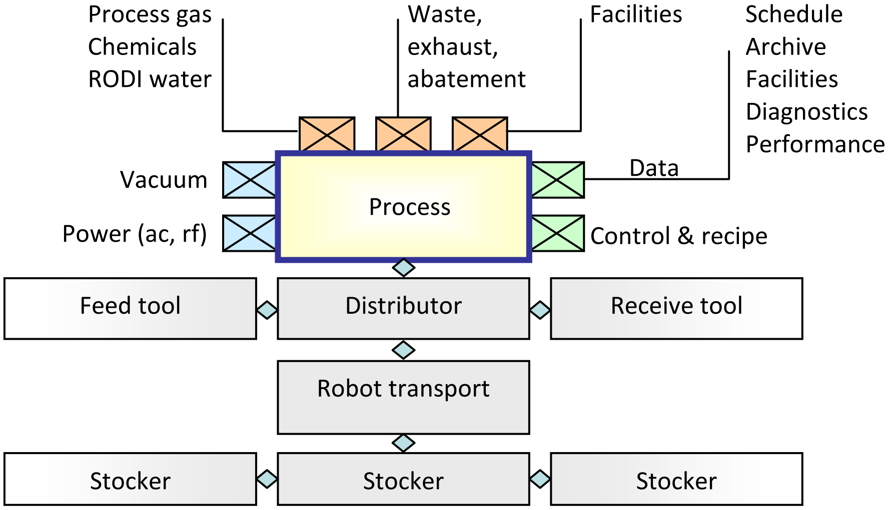

Figure 3. Generic layout of wafer processing tool

Within each tool, many hundreds of variables (and in some cases, several thousand) are continuously measured. Some data is used for closed loop control in the classical way. However, most is used to confirm that the intended process was followed and how the operational conditions varied even though everything stayed within specification. This process can routinely collect more than 100 MB per day per tool. The critical question is therefore what to do with massive quantities of data produced. An example for the case of semiconductor processing is illustrated in Figure 4.

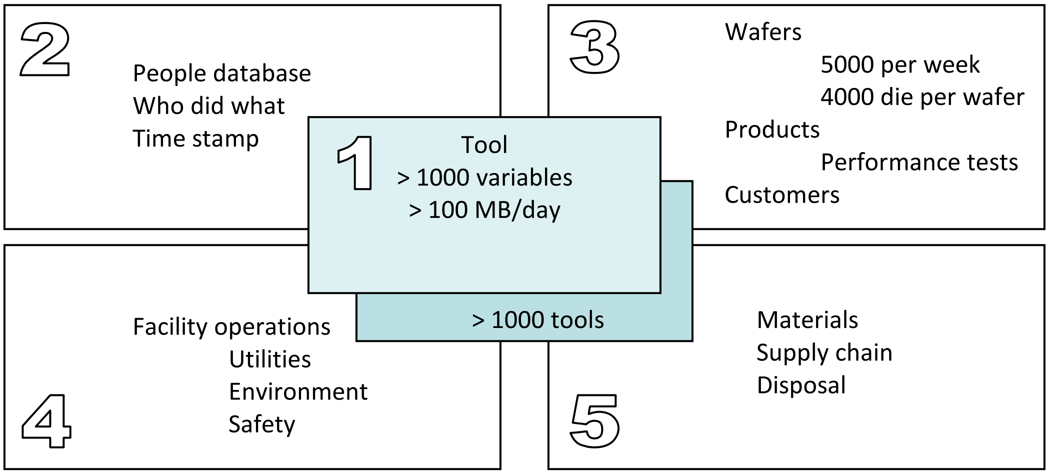

Figure 4. Interaction of five databases.

Manufacturing information is correlated with four other business operations databases. From a customer perspective, it means that it is possible to track the exact history of any one of a billion die produced by that plant every year. Over the past decade, software and hardware tools have been developed to structure and manage data on a TByte scale (and at reasonable cost).

Workplace implications

The three use cases are typical of what is happening in high-tech companies. They represent important extensions of measurement technology to:

- Validate simulation tools, especially under worst case conditions.
- Condition monitoring for system-level mission assurance.
- Provide an operational record to enhance performance, reliability and safety.

Although the examples refer to large and expensive systems, the trend is visible – and growing - in all electronic products, even extending to relatively low cost consumer goods. The changes do not affect the principles of measurement or good practice. All the old familiar technical problems remain. What has changed is the scale of measurement operations and their role within the product creation and support process. The amounts of data to be managed are now six or more orders of magnitude greater than even twenty years ago. Data is now also available to many more people within the organization and to customers. It is also possible to store and access the data at will into the indefinite future.

These changes are restructuring the workplace. Large, slow and labor-intensive test facilities are disappearing or being sent offshore. Test and measurement are no longer functions that are only performed occasionally. In their place, products and the process to produce them are equipped with embedded capabilities for continuous self-testing. The performance validation process is designed-in when a system is conceived. Signals that were once used only for closed loop control can now be separately collected and stored. The data can be used for continuous monitoring as in the missile case. It can also be used to create control algorithms that cannot be realized by traditional techniques. In a wider context, the availability of large data sets for product qualification has facilitated the more extensive use of sub-contractors and beyond that to international outsourcing. Without the qualifying data, these business practices would be very risky. The changes therefore impact almost every engineering function throughout the product life-cycle.

For those involved in the process of system design and validation, the important job features are:

- Plan all data acquisition and its management over the whole life of the product.
- Recognize that the quantity of data will be large.
- Organize the data structure to facilitate the way it will be used.
- Have consistent descriptions for all variables with complete supporting documentation.

- No mistakes with units and conversions.
- Build-in adequate scope for calibration and validation.
- Assume no data will ever again be lost or destroyed.
- Never assume that anyone else involved in the process is an expert or can discern any meanings that are not explicitly stated.
- Plan for technology change but with no break in operational availability.

With the global supply network that applies to most products, data is the blood supply that links all functions. It must therefore be kept clean and intact.

New technology as the driver for change

Semiconductor technology improvements over the past two decades have driven a quiet revolution in data acquisition products. In the 1980s, 8-bit accuracy was considered to be the best that could be achieved on silicon. Higher precision required much more expensive hybrid assemblies. Now we have 12-bit analog to digital converters as the input stages for $2 microcontrollers while 16 and even 18 bits are available [3]. The steady progression of digital technology is well documented in the International Technology Roadmap for Semiconductors (ITRS) [4]. It focuses mainly on the requirements for the minimum size devices that are required for state-of-the-art processors and memory. However, the same technology developments can have other benefits too. Matching of transistors and capacitors is the key requirement for analog designs, RFID tags, wireless coupling and integrated MEMS (micro electro-mechanical system) sensors.

In the typical data acquisition configuration shown in Figure 5, most functions (except those requiring the extremes of precision, accuracy and speed) can now be integrated on silicon. The whole system can be delivered with a few chips, sometimes within a single package and routinely on a single circuit board. That in turn implies low cost and higher reliability.

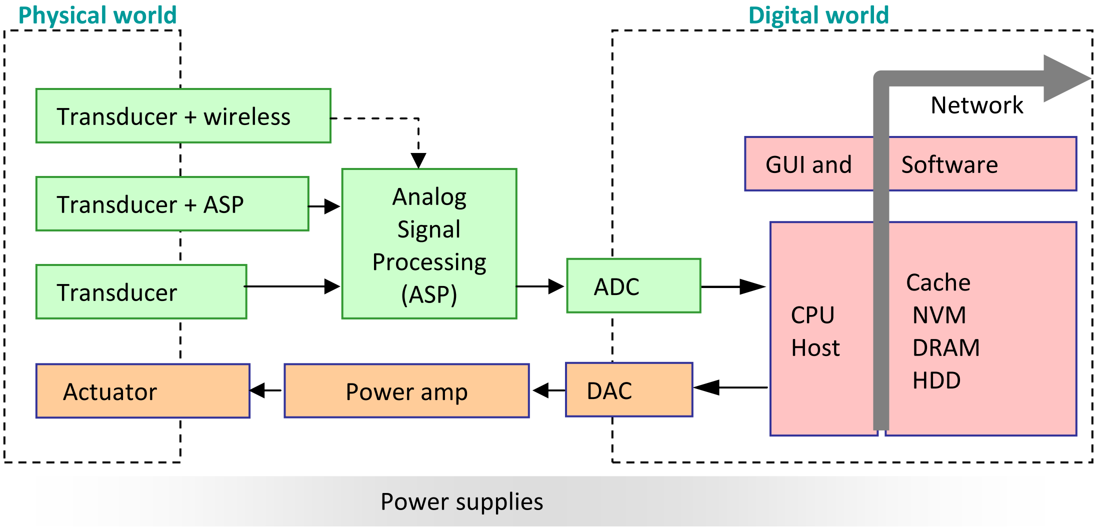

Figure 5. Typical data acquisition configuration

The functional features shown in Figure 5 have hardly changed in the thirty years since automated measurement became generally feasible following the introduction of the HP instrumentation bus and controllers [5]. However, the reduction in system cost by three orders of magnitude (or more) through integration on silicon has had a massive impact on how instrumentation is designed and used. Low cost encourages the construction of very large, massively parallel systems. This in turn leads to the productivity improvements behind the title of this paper. Thus an individual can manage tools that make billions of measurements in a very short time period at a cost of nano-$ each (or less). This is a new world for instrumentation and its practitioners. It requires new skill-sets that in turn place new requirements on curriculum content and emphasis.

Impact on skill-sets

The starting point to determine how these changes in systems applications should affect the curriculum is to identify the new or enhances skills that are needed. The main operational challenges are:

- Be clear about requirements for accuracy
- Identify and limit sources of drift that lead to loss of precision
- Clearly understand the environment in which the instrumentation must operate (temperature range, humidity, shock, vibration, etc.)
- Have a clear process for calibration and validation
- Make sure the instruments do not load transducers and transducers are matched to the output path
- Implement best practice in grounding
- Qualify noise sources and their impact on results
- Protect from electro-static discharges.

It can be a life's work to become expert in these techniques and they continue to be the bed-rock of good measurement practice. The skills apply equally to stand-alone instruments and automated systems. It is vital that academic programs at all levels continue to provide a sound foundation in these techniques. Technology may change but it can never correct for poor practical skills or systems that generate garbage.

Now consider what happens when an automated measurement process is introduced. The three use cases have shown that the list of skills has to be extended to include:

- System-level choices relating to speed, accuracy, cost and lifetime use.
- Automation of data acquisition.
- Management and representation of data in TByte quantities.
- System and data specification to match use patterns.
- Use of networks for calibration, monitoring and measurement control.

This combination of pre-planning and selection from a large menu of implementation options defines a whole new style of operation as shown in Figure 6.

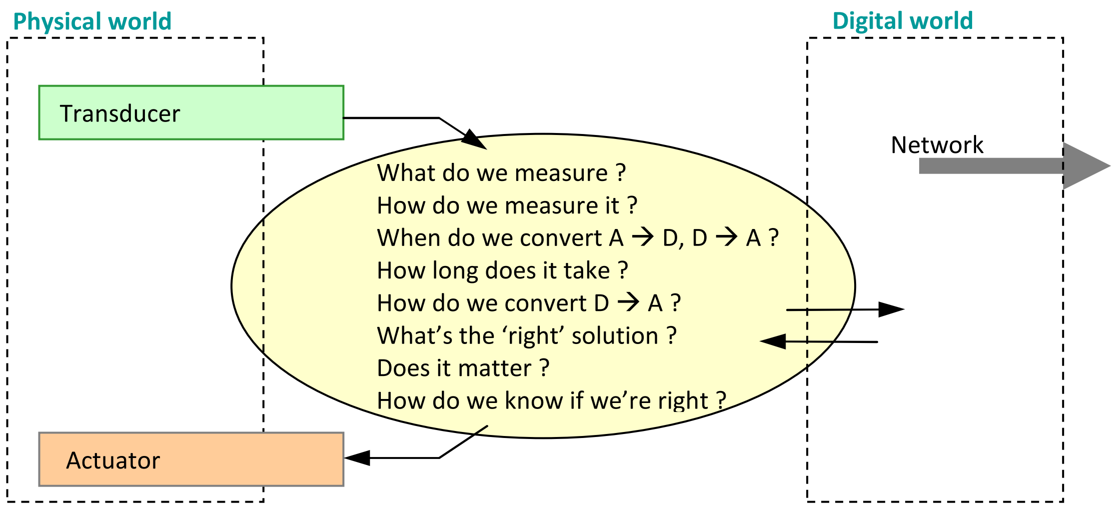

Figure 6. Decisions for automated measurement

Timing becomes a much more critical design parameter. Some typical issues are:

- Sampling rate for incoming analog signals
- Use multiplexed channels or parallel analog signal processing (ASP) lines
- Bandwidth of ASP channels
- Digital bus capacity into digital processing unit
- Digital bus capacity from the digital processor to the network
- How many parallel systems are required

The goal is to move into the digital domain as soon as possible. Typically, a microcontroller (MCU) [6] is used to create an embedded system. MCUs integrate signal conditioning, ASP, digital processors and increasingly large quantities of flash memory on one chip at very low cost. The combination of these effects is that measurement is no longer an expensive tool to be used sparingly. Every aspect of system performance can be measured continuously and the data can either be stored in local memory or conveyed to an external database. As a result, the whole approach to systems design is changing.

Curriculum implications

The previous discussion on skills shows that the traditional measurement topics in the curriculum remain as valid as ever. However, the implications of the vast increase in automated data collection throughout industry should also be recognized. Since data collection is an intrinsic part of new system design, the challenge cannot be simply waved off as "same concepts, more instances". How can these changes be accommodated in an already overloaded curriculum?

The solution adopted by the authors has been to insert some aspects of large-scale embedded measurement into every core course (freshman, sophomore and junior). By including a few high-level systems examples in every course, the contextual requirements for measurement and data can be covered. The tools, disciplines and electronic building blocks are common so repetition builds familiarity. This approach provides good examples of basic analog and digital measurement that can be validated on a small scale using microcontroller cards but at the same time related directly to large-scale industry applications of the kind discussed in this paper. The sequence being used is:

Freshman	Top-down system design and data requirements
	Use of units and the obligation for correctness
	Digital functions and timing for data transfer
Sophomore	Types of instrument and their realization
	Best practice in data collection
	Data representation - precision & accuracy
	Basic components of analog signal processing
Junior	Selection and performance of sensors
	Digital signal processing introduction
	Introduce microcontroller functions
	MCU application for automated data acquisition
	Constrained project to integrate learning outcomes

Curriculum changes are a work in progress that will continue to evolve over many years. However, they are built on close interaction with local companies and recognition that the character and purpose of measurement within the product applications space will continue to change rapidly. The importance of the topic is reflected in the skills and techniques that students acquire to be productive contributors to the next generation of advanced products and systems.

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