Validation for Micro- and Nano-Sensors

M. Henry[1]

University of Oxford, manus.henry@eng.ox.ac.uk

ABSTRACT

The rapid development of sensor and processing technologies is offering many opportunities for embedding new functionality within sensing devices. One important area is the development of diagnostics. While the generation of diagnostic error codes is becoming common, these can be difficult to integrate into a wider control system, and do not address the more fundamental issue of the quality of the underlying measurement. The SEVA (sensor validation) approach, which is now embedded in a British Standard [1], proposes that each sensor assesses the quality of each measurement value it generates, including the influence of any diagnosed faults, in order to generate an on-line uncertainty value. A variety of techniques can be used for validation. A micro-machined flow meter is considered along with a technique for exploiting redundancy among multiple micro- or nano-sensors.

Keywords: sensor validation, micro-machined flow meter, redundancy, uncertainty

1 SENSOR VALIDATION

The Sensor Validation Research Group at Oxford researches the application of digital technology to instrumentation, and to fault detection in particular. A model of how a ‘self-validating’ or SEVA sensor should behave [2] assumes the availability of internal computing power for self-diagnostics, and of digital communications to convey measurement and diagnostic data.

Currently, it is common for sensor diagnostics to be conveyed to the user via device-specific error codes (e.g. Fault 43 – coated electrode). While these codes are useful for maintenance purposes – the instrument technician knows what action is needed to correct the fault – this information is less useful for taking operational decisions. A plant with 10,000 sensors of 20 different types from 13 different vendors could face the generation of many thousands of different fault events, each of which needs to be interpreted from an operational point of view. For each potential fault event, can plant operation proceed, or must maintenance action be taken immediately?

The motivation behind the SEVA concept is to define a set of generic (i.e. plant- and instrument-independent) metrics for describing the quality of the measurement data, irrespective of the underlying fault mode (if any). This enables the development of generic strategies for responding to changes in measurement quality which do not need to interpret device-specific error codes.

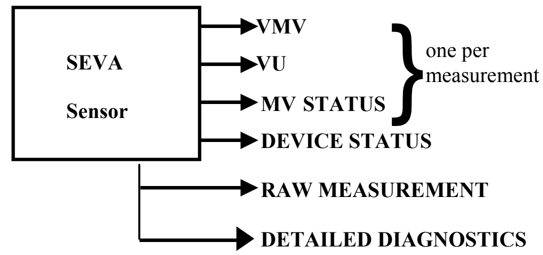

Fig. 1. Parameters from the SEVA sensor

A generic set of metrics are proposed for describing measurement quality (see figure 1). For each measurement, three parameters are generated:

- **The Validated Measurement Value (VMV)**. This is the conventional measurement value, but if a fault occurs, the VMV is a corrected best esti-mate of the true value of the measurand.
- **The Validated Uncertainty (VU)**. This is the metrological uncertainty, or probably error, of the VMV. For example, if the VMV is 4,31 g/hour, and the VU is 0,05 l/s, then the sensor is claiming that the true measurement value lies between 4,26 g/hour and 4,36 g/hour with 95% confidence.
- **The Measurement Value Status (MV Status).** Given the requirement to provide a measurement, even with a serious fault, the MV Status indicates how the current measurement has been calculated. It takes one of a small set of values, of which the most important are:
  - SECURE: based on redundant, fault-free sensors.
  - CLEAR: calculated normally.
  - BLURRED: raw data is still live, but the VMV has been corrected for some fault condition.
  - DAZZLED: a temporary state; it is known that current raw data is uncorrelated with the true process variable (e.g. the input is saturated), but it is not (yet) known whether the condition is permanent. The VMV is projected from past history, and the VU increases with time to reflect the reduced confidence in this projected VMV.
  - BLIND: as DAZZLED but there is evidence to suggest that the loss of raw data is permanent.

The VMV, VU and MV Status are generated for each measurement output from the sensor. For example, many industrial sensors measure process temperature as well as (say) flow or pressure. The validity of each is distinct, and each will be affected by a fault in a different way. However, for maintenance purposes, a single Device Status parameter is also provided, which indicates the level of maintenance action currently requested by the sensor (None, Low, High, Critical), alongside any device-specific detailed diagnostics.

The most important indicator of measurement quality is the on-line uncertainty of each measurement, the VU. It is calculated based upon all error sources affecting the on-line measurement, including:

- The transduction - the mapping from the true process measurand to the observed transducer signal;
- The components used within the instrument;
- The characterization procedure at the end of the production line, and/or calibration procedures;
- The operating point, and process noise;
- The effect of any faults.

Thus the VU provides information about measurement quality whether or not a fault has occurred. By contrast, diagnostics are only provided in the (hopefully) rare occurrence of a fault, and describe only the nature of the fault and not its impact on measurement quality.

In summary, SEVA maximizes the availability of the measurement by providing on-line correction for faults. It provides an estimate of measurement quality in a standard, generic form, thus enabling operational and maintenance decisions to be taken based on application-specific criteria, without detailed knowledge of the sensor fault modes.

2 EXAMPLE: CORIOLIS METER

Coriolis mass flow metering [3] has been established as the most accurate widely-used industrial flow measurement technology since its introduction in the mid 1980s. Coriolis meters operate by vibrating a flowtube (typically 1-300 mm in diameter) through which the process fluid flows. Two sensors monitor the flowtube vibration. The frequency of oscillation (typically 50Hz - 1kHz) is used to calculate the density of the process fluid. The geometry of the flowtube is arranged so that Coriolis forces act to give a phase difference between the two sensor signals, proportional to the mass flow of the process fluid (which may approach 1 tonne/s for the largest flowtube sizes). The so-called transmitter is the electronic device driving and monitoring the flowtube, and generating the measurement data.

More recently, micro-machined Coriolis flow transducers have been manufacturered [4,5], with flowtube diameters of 0.1-0.5mm, resonant frequencies up to 30kHz and flow rates down to 0.1g/hour.

The Coriolis meter was the first instrument to undergo validation analysis [2] by the Oxford group. Understanding of the fault modes fed into the design of a fully digital transmitter [6,7,8]. The resulting instrument [3] has become a commercial product, Foxboro's CFT-50. The use of all-digital technology has led to various performance improvements such as the dynamic response time of the same order of the period of oscillation e.g. 16ms [9]. In addition, the instrument is able to provide good performance despite fault modes which disable conventional Coriolis mass flow meters.

It is well-known that two-phase (gas/liquid) mixtures are very difficult for Coriolis meters to measure. A number of factors are at work, but typically, the high damping causes the flowtube to cease oscillation and hence no measurement is generated. This fault has industrial significance, for example in custody transfer applications where the meter may begin or end partially filled with air. The new meter developed by Oxford is able to maintain oscillation at high levels of two-phase flow. However, the physics of two-phase flow inside a vibrating tube causes inertial losses leading to mass flow errors [7]. Detection and compensation techniques have been developed which provide improved measurement of two-phase flows. However, the uncertainty of the resulting corrected measurement (typically of the order of 2%) is greater than that for a single phase fluid (typically 0.2%). Hence the provision of on-line uncertainty information is valuable in quantifying the reduced measurement quality during two-phase flow conditions. Fig. 2 illustrates the performance of the SEVA Coriolis meter with two-phase flow.

Prior to the injection of two phase flow (at about 5s) the measurement status is CLEAR, and the uncertainty band around the measurement is small, at about 0.2%. When air is injected into the process stream, the meter is able to maintain flowtube oscillation. The raw measurement (lower line) has an error of approximately 20%. Under the SEVA scheme the error is detected, the mass flow measurement is flagged as BLURRED, and a correction is applied. It can be seen from Fig. 2 that the corrected measurement (surrounded by uncertainty band) is a good approximation for the independently estimated true mass flow (dashed line). The uncertainty of the corrected mass flow rate is raised to approximately 2%. The generation of on-line uncertainty is valuable not only for taking operational decisions, but also in assessing the overall uncertainty of a batch, for example in custody transfer applications.

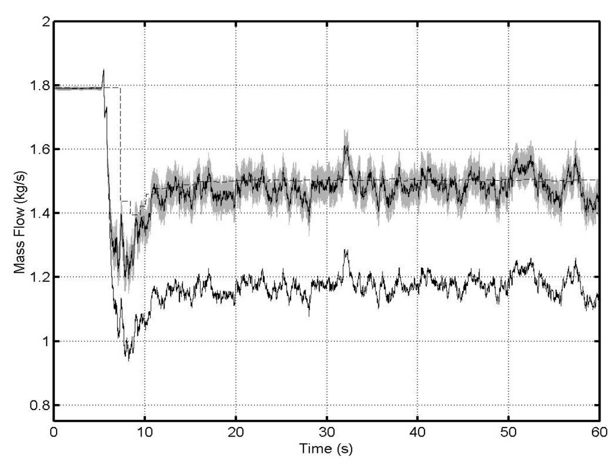

Fig. 2. Two-phase flow response of SEVA Coriolis meter

2.1 Micro-machined Coriolis metering

Oxford's digital transmitter technology is to be applied to a micro-machined Coriolis flowtube [4]. Potential benefits include a much faster step response time (target 0.1ms) and measurement update rate (also 0.1ms). Two-phase flow issues can occur at the micro-scale as well as in larger flowtubes, for example with gas coming out of solution as a result of pressure drop through the flowtube. Digital drive techniques will enable continuous operation through bursts of two-phase flow. Perhaps the biggest potential benefit is the generation of on-line uncertainty estimates, which could feed into quality assurance schemes for medical, pharmaceutical or other applications.

The primary challenge in applying digital transmitter technology to micro-machined devices is the much higher frequencies of oscillation used by these devices, entailing an order of magnitude increase in data and processing bandwidth. A new signal processing framework has been devised which will exploit the latest generation of FPGA hardware to deliver the required level of performance.

A second challenge is to assess micro-Coriolis flow measurements to traceable standards. The new three-year UK National Flow Programme includes a project to provide infrastructure for traceable measurements of ultra-low flowrates, and it is hoped to engage in that programme.

3 SEVA SENSOR FUSION

Ideally each sensor should provide complete diagnostic coverage. However, it may not economically or technically possible to ensure that all possible fault modes can be detected within the sensor itself. This is especially relevant for micro and nano-sensors with limited computational and diagnostic resources. It is possible to use the SEVA metrics to perform higher level consistency checking between redundant SEVA sensors to detect faults that cannot be diagnosed in the individual sensors themselves [11].

Figure 3 illustrates the scenario. Three identical SEVA sensors (for example redundant micro-sensors on a single chip), monitoring the same process measurand, generate SEVA metrics based on the limited diagnostics available in each. The combination block uses the SEVA data from each sensor to perform consistency checking between them, dealing with any outliers that are detected, and generating a Combined Best Estimate (CBE) of the true measurement value, and SEVA metrics associated with this estimate.

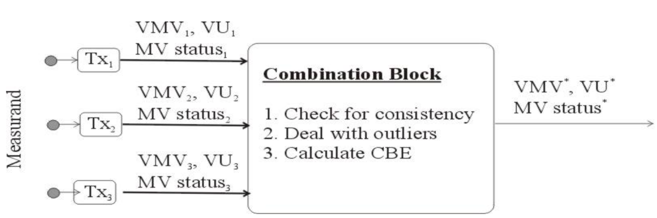

Fig. 3. SEVA Sensor fusion

There are many techniques that can be used for fusing data from multiple sensors. [11] presents a simple algorithm requiring no process modelling and which is suitable for implementation in a standard block such as might be used in an control system. All that is used are the properties of metrological uncertainty. Thus, given n estimates x_i of the same measurand with uncertainties u_i , and assuming all measurements are judged to be consistent, then the combined best estimate of the measurement x* is given by:

$$x^* = \sum_{i=1}^{n} w_i x_i \text{ where } w_i = \frac{(\frac{1}{u_i})^2}{\sum_{j=1}^{n} (\frac{1}{u_j})^2} \quad (1)$$

while the uncertainty of x* given by

$$u^* = \sqrt{\sum_{i=1}^{n} w_i^2 u_i^2} = \frac{1}{\sqrt{\sum_{i=1}^{n} (\frac{1}{u_i})^2}} \quad (2)$$

However, prior to combining measurements it is necessary to perform consistency checking. Moffat [12] suggests a calculation for two measurements only. This is based on a null hypothesis that the difference between the two measurements x_1 and x_2 should have zero mean. Thus x_1 and x_2 are Moffat consistent if:

$$\left| \frac{x_1 - x_2}{\sqrt{u_1^2 + u_2^2}} \right| < 1 \quad (3)$$

In order to identify which sensor is faulty, it is common to use at least three in a majority voting system. Assuming that faults are rare, the assumption is that if one sensor is inconsistent with the majority, then it is likely to be faulty.

Unfortunately, when extending consistency checking beyond two sensors, the Moffat test it is not transitive: if x_1 is consistent with x_2 , and x_2 is consistent with x_3, it does not follow that x_1 must be consistent with x_3. Thus, given a set of 3 or more independent measurements that need to be combined, two issues need addressing. First, the maximum subset of mutually consistent measurements must be found and declared the consistent subset. Second, the measurements outside this subset must be dealt with. It can be shown that the problem of finding the maximum subset of mutually consistent measurements is equivalent to the maximum clique problem in graph theory.

A linear algorithm is described in [11] providing an approximation to the maximum clique, together with techniques for smoothly reducing the influence of inconsistent measurements on the value and uncertainty of the CBE.

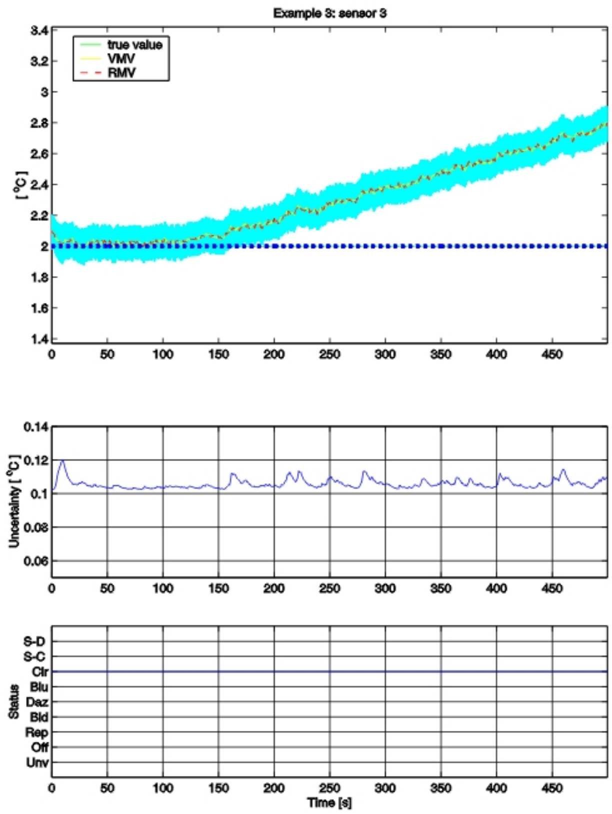

Fig 4a. Output of Faulty Sensor

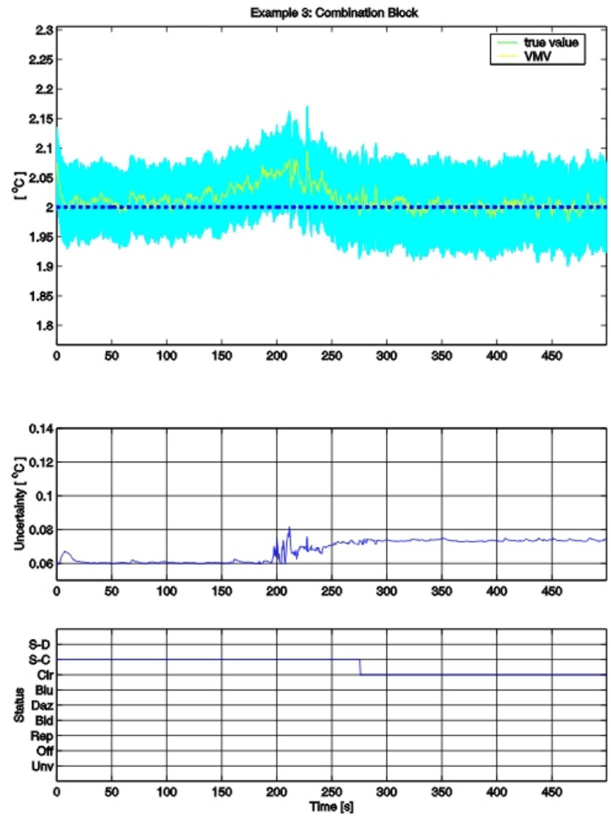

Fig 4b. Output of Combination Block

5.1. Simulation Studies

Figs. 4a and 4b show three SEVA sensors measuring the same process parameter, monitored using a sensor fusion block. A drift fault occurs in one of the sensors, which is not detected by the sensor itself. Fig 4a shows the output of the faulty SEVA sensor, which from time t=100s incorrectly drifts upwards, away from the true measurement value while its MV status remains CLEAR. Fig. 4b shows the corresponding output of the combination block. Initially the CBE also rises, but as the faulty measurement drifts away from the other two sensors (not shown) the CBE returns towards the mean of the fault-free sensors (from t=200s). The uncertainty of the CBE increases. Eventually, at t=275s, the output from the faulty sensor is labeled as permanently faulty, the CBE is based only on the non-faulty measurements and the MV status of the CBE is reduced from SECURE to CLEAR [11].

The combination block thus detects the inconsistent measurement, and generates a smooth transition in the CBE using the data from all three sensors to that of only two.

REFERENCES

[1] BSI (2005). "Specification for data quality metrics for industrial measurement and control systems", *BS7986:2005*. British Standards Institute, 389 Chiswick High Rd London W4 4AL.

[2] Henry, M.P. *et al*, (1993). "The Self-Validating Sensor: Rationale, Definitions and Examples". *Control Engineering Practice*, 1(4), 585-610.

[3] Henry, M.P, *et al*. (2000). "A self-validating digital coriolis mass-flow meter: an overview". *Control Engineering Practice*, 8(5), 487-506.

[4] Sparks, R. *et al.* (2004). Coriolis mass flow, density and temperature sensing with a single vacuum sealed MEMS chip, Solid-State Sensor, Actuator and Microsystems Workshop, Hilton Head Island, South Carolina, June 6-10, 2004.

[5] Clark, C, *et al.* (2006) "The dynamic performance of a micro-machined Coriolis flow meter", Nanotech 2006, Boston May 7-11 2006.

[6] Henry. M.P. *et al.* (2001). US Patent 6,311,136.

[7] Henry. M.P. *et al.* (2003). US Patent 6,505,519.

[8] Henry. M.P. *et al.* (2005). US Patent 6,950,760.

[9] Henry, M.P. *et al.* (2003). "Response of a Coriolis mass flow meter to step changes in flow rate". *Flow Measurement and Instrumentation*, 14(3), 109-118.

[10] NEL (2005), "Flow Programme Oct 2005-Sep 2008", Report No 2005/265.

[11] Duta, M., and Henry M.P (2005). "The fusion of redundant SEVA sensors". *IEEE Transactions on Control Systems Technology*, Vol 13, No. 2.

[12] Moffat, R.J. (1982). "Contributions to the theory of single sample uncertainty analysis". *ASME Journal of Fluid Engineering*, 104, 250-260.