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Simulating distributed measurement networks in which sensors may be faulty, noisy and interdependent: A software tool for sensor network design, data fusion and uncertainty evaluation

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ABSTRACT

We introduce a software simulation tool that can be used to study the measurement performance (both actual and intended) of sensor networks. The software, which is publicly available, is written in Matlab® with data read from an Excel® workbook, and may be used to investigate network performance, to compare different data fusion algorithms, and to evaluate the measurement uncertainties associated with aggregated data from networks.

The software can be used to simulate networks in which sensors are intermittently faulty or unreliable, varying levels of noise appear in the sensor outputs, and the sensor outputs possess interdependencies, that is, the response of one class of sensor depends on the quantity being measured by another class of sensor.

We set out a detailed account of our mathematical approach to simulating sensor networks and to data fusion and discuss briefly key features of the examples included with the software. We make recommendations for good practice in network design and choice of data fusion algorithm based on the examples, and discuss some of the limitations of our approach to data fusion applied to time series measurements.

1. Introduction

Sensor networks (both wired and wireless) are set to become a significant enabling technology in many areas of measurement, security and environmental monitoring. In the next decade industry will begin to benefit from the use of autonomous sensor networks that can, for example, determine their position and adapt to their environment. However, to exploit fully the potential of such networks a number of metrological issues relating to system reliability, calibration, uncertainty quantification and data fusion require consideration. In particular, there is a need for:

- Metrologically sound methods for quantifying and improving the robustness and reliability of sensor networks and related systems.
- Development of numerical indicators to represent the uncertainty associated with high-level aggregated outputs of such systems.
- Methods of handling missing data values in time series outputs of networks, including the consequences of missing data values for uncertainty quantification.
- Methods for treating the aggregation of sensor network time-series data, and undertaking the corresponding uncertainty evaluation, in a mathematically rigorous manner that takes into account correlations associated with measured values provided by the sensors.

Computer simulation of measurements made with sensor networks is a valuable tool that can be used to investigate the performance of networks and to compare data fusion methods. Simulation can take into account a range of aspects of sensor behaviour, including faulty or unreliable sensors, varying noise levels in sensor outputs, differences in sensor calibration information, and interdependency between

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different sensors. It can be used to evaluate the uncertainty associated with the estimate of the physical quantity of interest (the measurand) provided by each sensor, and to obtain an aggregated estimate of the measurand and the associated uncertainty when sensor data are fused. In addition, the outputs of different data fusion algorithms can be compared.

We have developed software that can be used both to evaluate uncertainties when sensor output data are aggregated and to assist network designers in specifying sensors and networks to meet their measurement performance aims. The methods we have developed are capable of generalisation to wide classes of time-series problems, and the software is extensible to many different application domains.

The paper is organised as follows. Section 2 introduces our approach to the simulation of networks, including methods for simulating the measurand and the sensing process itself, and the data fusion methods that have been employed. The mathematical details of these three topics are explained at greater length in the appendices to the paper. The examples that are included with the downloadable software are described in Section 3, with particular emphasis being placed on the Kalman filter example. The main body of the paper ends with brief sections setting out a discussion of some of the limitations of the work we are reporting here and a set of conclusions that make recommendations for good practice in choice of network simulation and data fusion methods.

2. Approach to the simulation

Our aim was to produce a suite of Matlab® [1] software modules with data read from an Excel® workbook to be used to study design of sensor networks and to investigate uncertainty in measurement networks. Users select the modules that are relevant to the task of interest and then combine them in a manner suitable for their application. In some cases it may be necessary for users to provide some additional code of their own. We have developed a set of examples that demonstrate how the software is used. The software itself, associated documentation and application examples, can be downloaded from the NPL web site at http://www.npl.co.uk/mathematics-scientific-computing/mathematics-and-modelling-for-metrology/software-downloads-(mmm).

2.1. An idealised measurement

We consider first a real-world measurement at a level of generality that may be applied to all measurands and sensors where the measurand varies with time. In the *real world* (as opposed to the *simulation world*) we assume that the measurand is an analogue signal that can be approximated by an analogue model, i.e., a model from which one can derive an exact instantaneous value of the measurand at any time of interest in a manner that is not limited by sampling and quantisation considerations. The model describes both deterministic and stochastic behaviour of the measurand. The analogue assumptions made concerning the measurand are also applied to sensors and to any noise that the sensing process itself generates. We therefore consider an idealised measurement that embodies the following stages:

1. Specification of an analogue measurand in terms of a mathematical model for its deterministic and stochastic behaviour.
2. Specification of analogue sensors and any associated noise. Each sensor produces a continuous electrical output, e.g., a voltage signal. The manner in which a sensor converts values of the measurand to values of the sensor output is described by a mathematical model, e.g., the calibration function for the sensor. The sensor may also be faulty. Faults may become evident at this stage or at later stages of the measurement process.
3. Sampling of each sensor output. The sampling process may be imperfect, and also introduce further noise effects such as jitter.
4. Quantisation of each sampled sensor output.
5. The quantised and sampled electrical output of each sensor is used to produce an estimate of the measurand and its associated uncertainty using the mathematical model in stage (2). If the measurement is regarded as dynamic, this stage may need to account for the frequency response of the sensor, and will typically be performed using a deconvolution algorithm [2].
6. Assuming that all sensors are measuring the same physical quantity, the estimates from the individual sensors are combined using a data fusion algorithm to produce an aggregated estimate of the measurand and its associated uncertainty. At this stage seemingly faulty sensors may be identified and excluded from the evaluation of the aggregated estimate and its associated uncertainty.

Our approach to developing the simulation software allows a user to include as many features of the above stages as are necessary to simulate the problem of interest. The software has been designed in a modular fashion to allow users to add their own modules to simulate particular features of the problem of interest. We therefore consider the software to be a toolbox that supports users in building their own solutions. Examples provided with the software demonstrate key features of the stages described above.

2.2. Simulating the measurand

Within the software the measurand is defined in the abstract, i.e., the user decides what is the actual physical quantity of interest, e.g., pressure, temperature, acceleration or humidity, and the units to be employed. Software modules are provided for simulating a measurand defined by an empirical model, e.g., a piecewise linear function or a Fourier series, or based on a physical model of the process generating the measurand. The values of the measurand can be contaminated by additive noise, which is restricted to Gaussian noise in the examples, but can be extended to other noise processes, e.g., described by power law or autoregressive models. The measurand may also be defined directly as a time history of discrete values. In whichever