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Multisensor data fusion in dimensional metrology

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ABSTRACT

Multisensor data fusion in dimensional metrology is used in order to get holistic, more accurate and reliable information about a workpiece based on several or multiple measurement values from one or more sensors. The theoretical background originates in classical mathematics and statistics, in methods of artificial intelligence (AI) and in the Bayesian fusion approach. Sensor technologies and sensor characteristics influence the data fusion process and determine the gain of information compared to the application of a single sensor. Homogeneous and inhomogeneous sensor configurations lead to complementary, competitive and cooperative information integration with specific advantages depending on the application. The scope includes image fusion, tactile and optical coordinate metrology, coherent and incoherent optical measuring techniques, computed tomography as well as scanning probe microscopes.

1. Purpose and basics of data fusion in metrology

1.1. Introduction

Since the requirements on the complexity and accuracy of dimensional metrology are increasing, multisensor data fusion methods are employed to achieve both holistic geometrical measurement information and improved reliability or reduced uncertainty of measurement data to an increasing extent. This paper reviews the process of data fusion and gives examples of its applications in dimensional metrology.

1.1.1. Definition

Multisensor data fusion in dimensional metrology can be defined as the process of combining data from several information sources (sensors) into a common representational format in order that the metrological evaluation can benefit from all available sensor information and data. This means that measurement results can be determined, which could not – or only with worse accuracy – be determined solely on the basis of data from an individual source (sensor) only.

1.1.2. Tasks and objectives

The basic motivation for multisensor data fusion is the improvement in the quality and usability of the measurement result, e.g. in a production process. Measurement of (often multivariate or complex) quantities is enabled which are not accessible with single-sensor systems. This additional metrological benefit may be termed synergy. Synergistic effects may improve the performance of a system in at least one of the following ways: increased spatial and temporal coverage and better resolution, increased robustness to sensor and algorithmic uncertainty, better noise suppression and improved accuracy [48]. Particular features of a workpiece can be measured with the most suitable sensor, and measurements with small uncertainty can be used to correct data from other sensors which exhibit relevant systematic errors but have a wider field of view or application range.

1.1.3. Characteristics of information sources

Sensors of a similar type which capture the same or a comparable physical measurand are called homogeneous sensors. An example is the use of cameras with different observation parameters. On the other hand inhomogeneous sensors acquire different characteristics of a scene. Here the information is not directly linkable and pre-processing is necessary (e.g. feature extraction, classification, data compression). An example is the fusion of greyscale images and 3D-data.

1.1.4. Sensor configuration

Multisensor fusion describes the synergistic application of different (homogenous and inhomogeneous) sensors to perform a given measuring task. The kind of integration of multiple sensors into a multisensor system depends on the application and the kind of sensor data or signal (Fig. 1).

Durrant-Whyte [46] classifies a multisensor data fusion system after its sensor configuration in the categories competitive, complementary and cooperative integration.

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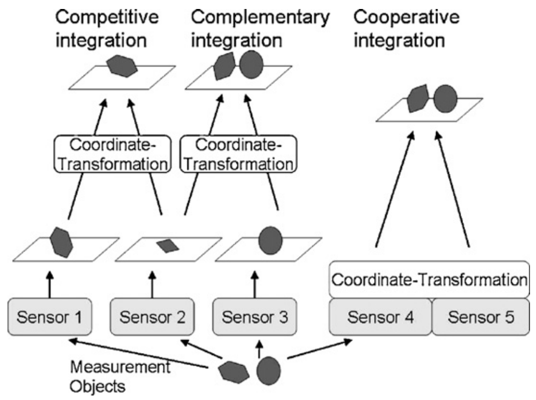

Fig. 1. Methods for data acquisition. Based on [160].

A sensor configuration is called complementary if the sensors do not directly depend on each other, but can be combined in order to give a more complete image of the phenomenom under observation. Complementary sensors help to resolve the problem of incompleteness. An example being images captured by homogeneous sensors with varying distance to the object surface showing different locations on the surface in focus according to the height of the surface. The locations, which show the highest contrast, are then fused for the final result [150]. Other examples are the fusion of images captured with different illumination series to achieve images with higher contrast [81] or the stitching of images captured by one or more moving or motionless cameras [135].

A sensor configuration is competitive if each sensor delivers an independent measurement of the same property, e.g. an image sensor captures data from the same measurement area and the redundant information is fused by evaluating the mean for each pixel. Thereby all images of the series contribute equally to the fusion result [85]. The aim of competitive fusion is to reduce the measurement uncertainty and to avoid erroneous measurements.

A cooperative sensor configuration uses the information provided by two, or more, independent (inhomogeneous) sensors to derive information that would not be available from the sensors individually. The evaluation leads to increased information of object details and an elimination of ambiguities. Often, cooperative sensor configurations allow measurands (multivariate or multi-dimensional) that could not previously be evaluated to be measured. A practical example would be the case of multisensor coordinate measuring machines (CMMs) integrating different high precision sensors such as optical and tactile sensors and computed tomography.

1.1.5. Data sets (point clouds)

Data sets can be classified with reference to their origin or source and, hence, with physical measurement information they represent. In dimensional measurement, relevant examples are given with

- Intensity images (e.g. from CCD cameras)
- Surface descriptions (e.g. tactile or optical sensor data)
- Volume data (e.g. computed tomography (CT)- or MR-magnetic-resonance data)

If data sets represent points on the surface of a workpiece or of a feature, they are often named "point clouds".

1.1.6. Classification in accordance with fusion aspects

Boudjemaa and Forbes [15] classify the data fusion problems according to the aspect the data is fused:

- Fusion across sensors
- Fusion across attributes
- Fusion across domains
- Fusion across time (filtering)

Fusion across sensors: A number of sensors nominally measure the same property, such as, e.g. a number of tactile and optical sensors measuring the dimension of an object obtaining two or more volume data sets.

Fusion across attributes: In this situation, a number of sensors measure different quantities associated with the same experimental situation. Consider, for example, the measurement of the length of a gauge block by a laser-interferometric system. The displacement measured by the interferometer depends on the refractive index of air which in turn depends on air temperature, pressure and humidity [14]. The length of the gauge block also depends on its own temperature which also has to be monitored. Thus, in order to determine the gauge-block length, up to five sensors are required to capture all relevant input quantities such as interferometer fringe counts, air temperature, air pressure, humidity and artefact temperature.

Fusion across domains: A number of sensors measure the same attribute over various ranges or domains. This arises for example in triangulation or photogrammetry. Another example is the fusion of two images of an object taken from different viewpoints under different illumination conditions. In such cases the desired information can only be obtained by combining a series of images, yielding a new or an enhanced representation of the image contents or characteristics [173]. Another example is the fusion of data sets of two or more range images of an object taken from different viewpoints (e.g. to overcome limitations of optical sensors on the maximum detectable slope [122,123]) or data sets of different dimensions (e.g. intensity image and range image).

Fusion across time: New measurement data are fused with historical information, which, for example, could originate from an earlier calibration. Often the current information is not sufficient to determine the system accurately and historical information has to be incorporated to achieve this. This fusion across time is realized, for example in predicting filtering in dynamic measurement (parameter estimation of dynamic systems), such as in Kalman filters. Further examples: Two range images of a moving or vibrating object taken from almost the same (relative) viewpoint but at different times or sequentially measured volume data sets of the same object measured by the same device (filtering).

Two further classifications for data fusion are

- Fusion for information gain
- Fusion for information evaluation

2. Theoretical aspects of multisensor fusion and integration

Multisensor data fusion based on different information sources involves the following operations:

- Pre-processing
- Registration
- Optimization
- Data fusion
- Data reduction (optional)
- Meshing (optional)
- Data format conversion (optional)

As first step the sensor data typically is pre-processed at the necessary level of abstraction. Afterwards the sensor data are transformed into a common coordinate system (registration) evaluating items such as features. Before the final data fusion an optimization is run, taking *a priori* knowledge into account. The optimization results in an 'instruction' of how the fusion result is to be achieved based on the measuring data and additional knowledge.

2.1. Pre-processing at fusion levels

In data fusion information can be raw data provided by multiple sensors as well as a mathematical interpretation