Calibration for Industry 4.0 Metrology: Touchless Calibration

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Abstract. Industry 4.0 denotes the fourth industrial revolution introduced in 2011 at the Hanover Fair, which already started to change the manufacturing industry. In the paper an original concept of the calibration process of Industry 4.0 measurement equipment by a touchless calibration system (TCal) is presented. The described approach can be realised by providing synchronized communication in real time between the calibration laboratories and clients’ laboratories for calibrating instruments which are remotely located from the reference standard used in the calibration process. The objective is to gather information parameters from the calibration reference standard and send them by digital network to the unit under test (UUT-the calibrated item). The overall calibration procedure has to be totally synchronized (data, sensors and environment), so the calibration process would keep the requested accuracy as done in “a single room”, i.e. in the calibration laboratory or on-site in the clients’ premises. Application examples are presented as well as an analysis of the contributing factors to the uncertainty budget in the Industry 4.0 calibration measurement systems is conducted.

1. Introduction
The realization of legal and industrial requirements for calibration and traceability of measurements [1], [2] can be achieved through complex processes in calibration hierarchy. The traditional calibration process is based on sending the calibration artefacts from one place to another, which is effective, but not efficient. It is time and cost-consuming with the ever present risk that the calibration artefact could lose its specifications/accuracy during the transport. If the calibration (reference) laboratories and client laboratories can be connected by means of data transport, instead of instrument transport, then the overall calibration process can be done on-line and in real time: the data electronically transferred from one place (BIPM, National Metrology Institute-NMI or calibration laboratory) to another (secondary calibration or client laboratory) will allow a calibration process in different locations without bringing the calibration reference standard and the unit under test (UUT-calibrated item) at the same place, i.e. in the calibration laboratory or on-site in the clients premises by physical transporting of a mobile reference standard in the vicinity of the UUT. So, both time and money will be saved. It can be achieved through establishing a procedure to produce, transfer and control calibration data which will compare the values of the reference standards to the values of the UUT without endangering accuracy and traceability necessary for calibration.

2. Industry 4.0
Industry 4.0 (IND4.0) denotes the “fourth industrial revolution”, [3-5]. As a concept it was promoted in 2011 by the German Government. It was accepted worldwide as something which changes today’s manufacturing world. It is based on digitisation and robotics process which could integrate companies
(inside and outside) in production and logistics [3]. It is achieved by intelligent solutions and digital networking, ensuring very fast and reliable data transfer of all embedded systems with new structure named Cyber-Physical Systems (CPS). The CPS is based on Information and Communication Technologies (ICT) which transforms the virtual and the real worlds in order to create networks where subjects and objects intelligently communicate and interact with each other. Overall evolution of system technology is given in Figure 1. The foundations of IND4.0 are mini (“smart”) computers embedded into the CPS [3]. These mini computers process information gathered through sensors and they are capable to determine and measure the present state of both equipment and processes, to analyse the situation and to trigger particular actions which improve the overall state. This is done through a superior linking of hardware and software by new digital networking. The CPS is capable for control, automation and regulation of processes and systems remotely and in real time. The main metrology requirements in connection to IND4.0 are: time and cost efficiency, easy handing, real time execution, automation and high speed [4], [5]. According to these requirements, the IND4.0 road map for metrology development is based on five aspects: Fast, Accurate, Reliable, Flexible and Holistic.

**Figure 1: Technology evolution triggered by Industry 4.0**

3. Touchless Calibration - TCal

The concept of touchless calibration (TCal) is based on the transport of calibration data to the calibration laboratory instead of the UUT (instruments) themselves. If this calibration data can be transformed into a digital message transferred remotely from calibration laboratory with particular accuracy, then the calibration process can be done both effectively and efficiently in some other place without the UUT and reference standards being in physical connection. The concept of TCal is described Figure 2. The TCal system consists of three main parts: a Transmitter, the IND4.0 Network and a Receiver. In all of these parts, there are devices based on “smart” CPS with powerful configurations allowing them high speed data transfer and reliability and integrity of data processing, calculations and operations. The Transmitter is situated in the reference calibration laboratory with the requested calibration reference standard. It consists of a few integrated parts. The calibration reference standard is an obligatory item. It could be a primary, secondary or any other standard used as reference standard for calibration. The Sensor&Transducer (S&T) is the main part. It is a CPS device capable of measuring value(s) of the calibration reference standard and transforming it into electrical signal(s). These electrical signals (equivalent to the calibration data necessary for the calibration process) are submitted to the Tx Processor. Synchronized with the S&T operation, the Environmental Sensor measures and submits the environmental conditions (values of temperature, pressure, humidity, etc.) of calibration laboratory to Tx Processor. The electrical signals of the calibration and environmental data are processed and transformed by the Tx Processor into calibration message and this message is sent to the I/O device. This device is actually standardized gate of the communication channel for the IND4.0 Network. It transforms the calibration message into a standardized IND4.0 message and sends it to the Receiver. The IND4.0 standardized message depends on the communication protocol used and it comprises the calibration data, control data and parity check data for improved reliability and integrity. The Receiver is receiving the standardised message from the Transmitter by its own I/O device and processes it through the Rx Processor. Calibration data, control data and parity check data are extracted from the message. The calibration data is checked for errors by the parity check data and then divided into calibration and environmental data. The calibration data in the Rx Processor are divided into calibration and environmental data. The calibration data is checked for errors by the parity check data and then divided into calibration and environmental data. The environmental data in the Rx Processor are transformed into a format which allows a comparison with the data taken from UUT. At the same time, the Rx Processor transforms the environmental data into an appropriate format which will be submitted as a signal to the Environmental Sensor&Actuator (S&A). This device adjusts the environmental condition in the laboratory at the same values of the client laboratory and keeps them in
accordance with the environmental conditions in the reference calibration laboratory. The S&A measure the values of the UUT and produces an electrical signal. This signal is submitted to the Rx Processor and is compared to the received data from the reference standard. The difference between the data is registered and processed in order to calculate errors and the instrument uncertainty. If necessary, the S&A adjusts some parameters of the UUT by the request of the Rx Processor. It can be noticed that on the Transmitters side, the flow of signals (data) is one directional and on the Receiver side is bi-directional. The reason for that is the fact that the calibration process is conducted on the Receiver side and all comparisons and adjustments are done here based on data from Transmitter side. This means that the Rx Processor must be superior in speed and capacity to the Tx Processor.

![Flow-chart for Touchless Calibration (TCal)](image)

**Figure 2: Flow-chart for Touchless Calibration (TCal)**

4. **Application of TCal and Analysis of the Uncertainty Budget**

The main challenge/objective is to achieve accurate transfer of reference calibration standard data to the UUT in the TCal process. The data measured from the Reference Calibration Standard on the Transmitters side should be plausible, accurate and precise when transferred to the UUT on the Receivers side. The total uncertainty, in general, consists of traditional uncertainty sources of particular calibration method which consists of systematic and random uncertainties. Considering that this concept is applicable for IND4.0 digital networks, some of the already known contributing factors to the total budget of uncertainty will disappear due to particular design of the calibration method for TCal. Namely, some of random uncertainties due to process automation should vanish. However, the digitalization of the process will bring new random uncertainties which can be calculated by Monte Carlo and Bayesian methods applied to analyze errors in the transfer. Anyway, the new design introduces new influential factors which will appear due to the sensing and the transmission processes of the calibration data. The total uncertainty may be expressed by sum of variances ($\sigma^2_{tot}$) of traditional ($\sigma^2_{trad}$) and uncertainty sources introduced by the TCal concept ($\sigma^2_{TCal}$):

$$\sigma^2_{tot} = \sigma^2_{trad} + \sigma^2_{TCal} = \sigma^2_{trad} + (\sigma^2_{dc} + \sigma^2_{ir} + \sigma^2_{env} + \sigma^2_{sp} + \sigma^2_{dev}) \tag{1}$$

The measurements of the values derived by the Reference Calibration Standard and by the UUT shall be done (as much as possible) by identical sensors. So, $\sigma^2_{dc}$ is a variance caused by the difference of the sensors characteristics. The calibration data produced by the S&T must be interpreted by the S&A in the same way and the requested accuracy and uncertainty of calibration has to be fulfilled. So, the sensors implemented in the S&T and the S&A must have same characteristics: they need to be paired. MEMS should have considerable role in this area. As an example, for the calibration of weighing instruments, the piezoelectric crystals as sensors could be used. These sensors transform mass into voltage and vice versa. The Reference Calibration Standard of 1 kg is put on S&T and its piezoelectric
sensor produces a particular voltage. This voltage is processed by the Tx Processor, transformed into calibration data and together with the environmental data are sent through the IND4.0 Network to the Receiver side. The pairing of piezoelectric sensors in the S&T and S&A can be achieved if they are manufactured from same piece of piezoelectric crystal. An accurate manufacturing process can produce well paired characteristics of the piezoelectric crystals with very small difference in parameters. The transfer of the measurement message from the Transmitter to the Receiver could cause the next contribution to the total uncertainty - $\sigma^2_{tr}$. It is realistic to expect that some of the message accuracy could be lost. However, if the transformation is done by a superior A/D and D/A conversion, it can be reduced to an extent not to increase significantly the total uncertainty. The data transfer through IND4.0 Network should produce no problems because it is digital transfer which is extremely reliable and with high integrity. In general, $\sigma^2_{tr}$ could be neglected. The discrepancy of the environmental conditions in the reference calibration laboratory site and the client’s site is the third source of uncertainty. The environmental sensor on Transmitter side and the environmental sensor (part of Environmental S&A) on the Receiver side must be of same type and be paired. In order to produce the same and stable environmental conditions on both sides (Transmitter and Receiver), any uncertainty expressed by $\sigma^2_{env}$ regarding the environmental conditions has to be as small as possible. The speed of communication through the IND4.0 Network is source of the fourth influential factor to uncertainty $\sigma^2_{sp}$. To simulate a “single room” calibration, it is necessary to provide the highest possible speed of communication in order to satisfy the dynamics of eventual variations of the calibration and environmental conditions. Every change of some parameter in the calibration room must be transferred as fast as possible. This might not be a big problem and it depends mostly on equipment used. Nevertheless, considering that each CPS device is a “smart” computer supported by very fast network (provided through the IND4.0 concept), the speed of operations of the equipment should be able to fulfil all calibration requirements. The last variance article $\sigma^2_{ev}$ is caused by eventual data errors which each device involved in the process could introduce to the calibration process. By considering the digital technology used and available, this uncertainty will be small enough to satisfy the calibration requirements.

5. Conclusion
The presented methodology of transferring a “number” for calibration all around the world, instead of sending the measurement instrument far away, is a concept, which can be realized if all aspects of Industry 4.0 are fulfilled. Some researches and further development in this area should support the standardization of sensors and other equipment, but everything could be done under the umbrella of the Industry 4.0 implementation. However, the process of validation of the methodology has to be accomplished. As a result of these and further researches in the field of metrology for Industry 4.0, calibration data by BIPM or NMI reference laboratories could be published, which could be used by laboratories and companies to do calibration in real time. This could lead to a new revolutionized form of cost effective real-time calibration procedures.

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