Metrological Data Completeness for Digital Transformation

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***Abstract*—Previous work has economically motivated and proposed a measurement information infrastructure (MII) as a means of digitally transforming the measurement information economy and enhancing interoperability within the international quality infrastructure's context. The NCSLI 141 MII & Automation Committee has identified metrological documents to digitalize and has proposed several MII-document design requirements. One design criterion, data-completeness, intends to ensure that MII documents include all information available on a calibration and measurement capability, measuring system, or measurement result. This paper argues that such data completeness will enhance digital documents' economic and metrological value relative to simply digitalizing existing work flows that omit information considered burdensome for manual processing. The paper considers digital enhancements to traceability, modeling, and numeric precision relative to non-digitalized documents and suggests more complete content.**

***Index Terms*—digital transformation, MII, metrology, traceability, IoT, instrument model, instrument specification**

I. Introduction

Business and industry worldwide have enthusiastically embraced digital transformation[1]. A huge information economy has arisen to produce and consume the consequent data, creating a demand for automatic data exchange and processing. That demand remains largely unsatisfied within the international quality infrastructure (IQI), with particular economic pressure on IoT sensor deployment. This conference, for example, has a number of special sessions investigating nontraditional ways to maintain, augment, or replace IoT sensor traceability.

IoT adoption without traceable calibration (interoperability via sufficiently low uncertainty) increases risk and undercuts credibility and public trust [1]. The IQI provides the desired interoperability but has fallen far behind the digital technology curve, thus incurring relatively high (labor, e.g.) cost and limiting its value, especially for ubiquitously deployed, low-cost IoT measuring instruments. Burdensome interoperability costs motivate sensor deployment without (periodic) calibration, pushing the optimum economic operating point toward less traceability and increased risk. The measurement information infrastructure (MII) initiative, and digital transformation in general, seek to shift the cost curve and optimum operating point toward decreased risk and cost.

This paper relates ongoing MII development and goals to data interoperability concepts that will help Industry 4.0, IoT, and the wider IQI to flourish in a digitalized context. In particular, the paper addresses the MII's data-completeness concept with intent that IQI digital transformation succeeds by fully—not partially—transforming data flows.

Section II summarizes the MII context and details the data-completeness design requirement. Sections III and IV discuss data completeness for measurement traceability and instrument modeling, respectively, as primary examples. Section V emphasizes the human aspect, and VI concludes the paper.

II. A Measurement Information Infrastructure

To provide context for the data completeness design criteria, we provide here a brief MII background. Previous work has described the MII concept and vision [2], economic motivation and available technology [3], and relation to IoT [1]. A web site [4] provides complete information. Defined as

> **MII**
> —set of normative standards that unambiguously define data structures, taxonomies, service protocols and security for locating, communicating and sharing measurement information [5],

it represents a digital transformation for metrology via which all measurement computing systems might intercommunicate without any manual data processing, interpretation, transcription. Such an MII would standardize measurement data exchange but not data processing procedures, leaving software development and innovation free to provide unforeseen benefits. The following sections briefly summarize MII digital documents and introduce the data completeness concept.

A. MII Documents

Fig. 1 shows the three core document types that conduct measurement information between entities in the measurement information economy: instrument specifications, accreditation scopes[2] (SoAs), and test and calibration certificates. We intend

[1]In this paper, digital transformation refers to digitally storing, transmitting, and leveraging data to enhance or create products and services and replace physical artifacts or optimize their utilization. In contrast, digitization simply concerns converting analog data (e.g., human-readable paper, PDF, etc. documents) to binary form. Digitalization means automating processes around tagged digital information (e.g., automatically exchanged machine-readable documents).

[2]An MII SoA will also represent unaccredited laboratories' capability statements or those from national metrology institutes.

these MII digital documents to support automated searches based on end-user measurement requirements for interchangeable instruments with interchangeable calibrations purchased from laboratories selected from interchangeable calibration and measurement capabilities (CMCs).

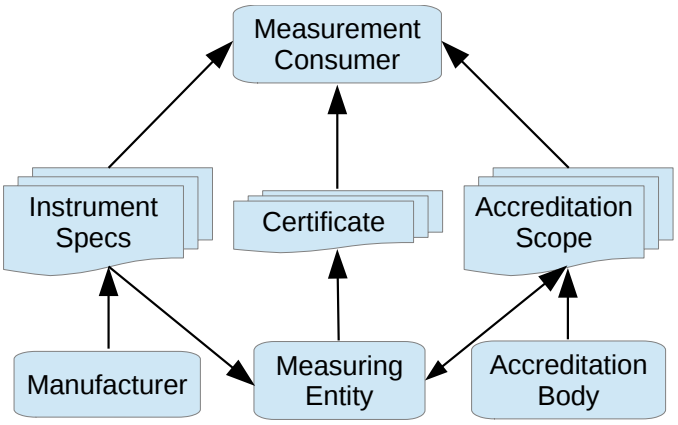

Fig. 1. Partial information flow in the metrology economy, adapted from [3].

All three documents revolve around measured quantities and therefore lend themselves to modular data models. For strict machine interoperability, the corresponding MII document models [4] specify the commensurate metadata elements (qualifiers, conditions, measuring intervals, influence and input quantities) to adequately communicate the measurand and measurement quality metrics (MQMs) such as maximum permissible error (MPE) or uncertainty. The subsequently developed MII SoA XML schema [6]–[8] implements the SoA model, with instrument specifications and calibration certificate schemas yet to come. Table I gives an overview of the core data elements.

TABLE I
MII CORE DATA AND METADATA

Metadata Modules	Submodules and Data Elements
administrative data	organizations, services, localization, identifiers, authentication, approvals, registrations, configuration management
instrument data	measurement functions, measuring ranges, influence quantities, input quantities, measurement model, automation commands
operating conditions	rated, reference, storage, transportation, and operation quantity value intervals
measurement data	measured, nominal and reference values, traceability, bias correction parameters, MQMs, environmental conditions
uncertainty data	coverage intervals and probability, distributions, degrees of freedom, correlations, Monte Carlo results

B. Document Design Requirements

Summarizing [1], the MII design requirements include:

- Standardization—The SI, VIM [9] and other norms should inform the data models.
- Interoperability—Machine-readable metadata (complete measurand descriptions) should describe all MII data so as not to rely on context manually acquired elsewhere.
- Data Completeness—MII documents should retain all measurement information rather than discarding detail not deemed suitable or practicable for manually processed analog documents.
- Identity—Every reusable element, from small details to the document itself should have a unique identity code.
- Extensibility—The document versioning and underlying data structure and encoding should ensure forward and backward compatibility for new, updated, and deprecated information fields' long-term functionality.
- Authentication and Authorization—an MII document should bear security features to authenticate its originator and restrict access to authorized parties as applicable.
- Revocation—Issuing authorities should have a mechanism to revoke MII documents when appropriate.

We now focus on the data-completeness concept.

C. Data Completeness

Mechanization shifts the cost curve and makes impracticality practicable. We should therefore not hold future automation opportunities hostage to pragmatic manual practices that drop information or take shortcuts. Digital transformation will benefit the IQI more than simply digitalizing current practice.

For the advantage of downstream computation and the value generated, MII documents should retain all available data and metadata potentially useful at any present or future time: correlations or covariances, upstream traceability data, Monte Carlo distribution outputs, optimal specifications, full numeric precision, and other information as security and appropriateness determine [1].

A trivial but philosophically important example illustrates the manual-to-automated, analog-to-digital paradigm shift: numeric precision. Current practice [10], [11, e.g.] recommends pragmatic numeric rounding conventions applicable to paper and other manual or analog tools. Rounding adds no significant value in a digitalization context[3]; it merely increases numeric error and uncertainty, software complexity and bugs, etc. [12].

Though software should adhere to requirements when displaying or printing data for analog records, the digital-document data-completeness principle rejects all internal rounding in either final or intermediate results; indeed, unforeseen applications may benefit from unlimited precision or symbolic rational number[4] representations. This extends the various guides' advice, e.g., "…in some cases…retain additional digits to avoid round-off errors in subsequent calculations" [10, §7.2.6], from single documents to the entire traceability chain. That said, we move on to more significant data-completeness issues: traceability and modeling.

[3]Caveat: Variable-precision computing research seeks ways to optimize precision in high-performance, energy- and time-intensive computing.

[4]For example, $1/3$ rather than $0.333\ldots$.

III. Traceability

Today we may verify a calibration's IQI suitability by inspecting the accreditation mark, checking the laboratory's and accreditation body's scope and status, and comparing the certificate to contractual requirements. Beyond that, however, we may find an analog certificate's information insufficient for advanced analysis. Quoting from the GUM [10, §7.1.4]

> Although... the amount of information... to document a measurement result depends on its intended use, the basic principle... remains unchanged: when reporting the result... err on the side of providing too much information rather than too little.

The GUM further recommends that measurement data include measurement results and uncertainty calculation methods, the full uncertainty budget and derivation, sufficient information to duplicate the results, and all corrections, constants, and their sources. Depending on the customer and IQI traceability level, many certificates omit one or all these recommended elements, especially when handling multi-function instruments with hundreds of measurands. This perhaps should not surprise us; our term "traceability chain" implies a single straight path to the SI, but in practice traceability from products to the SI comprises a vast, complex graph network. We may excuse most current practice based on the phrase "depends on its intended use" since most measurement-data consumers lack the systems to economically digest the missing information. Various proposals and existing systems, however, seek to rectify this situation.

A. Minimal Representation

One proposal [13] outlined a compact format and commensurate uncertainty calculation for reporting covariance information. Prior work [14], however, had demonstrated software that encapsulated error-source data in "uncertain numbers" to transparently compute uncertainty, while tracking all upstream covariance and passing this information downstream for further use. Some microwave calibration laboratories already use the *Metas.UncLib* [15] software, which built upon [14]. The original MII technical proposal [12] outlined a similar scheme around the notion of an uncertainty vector space, specifically for MII certificates.

These concepts revolve around uniquely identifying independent (orthogonal) base quantities (BQs) from which all reported measurement results derive. In the data, each measurement result structure contains a list of sensitivity coefficients (SCL) with respect to the BQs on which it depends, along with those BQs' identifiers (IDs). When a calibration combines traceable input quantities via a measurement function to produce a new measurement result, the process also computes a new SCL from the measurement model and the input quantities' SCLs, packages the new SCL with the new measurement result, and appends any new uncertainty sources to the BQs. The IDs serve to correctly combine common influences, thus correctly accounting for covariance per [10].

Table II illustrates the process: Input quantity A from certificate A depends on BQs 1 and 2; input quantity B from certificate B depends on BQs 2 and 3. New certificate N's SCL combines SCLs A and B, adding a new BQ (4) representing a new uncertainty source. In general, $c_{N,i} = c_{NA} * c_{A,i} + c_{NB} * c_{B,i}$, where $c_{X,i}$ gives the sensitivity of SCL X on BQ i and c_{YX} the sensitivity of quantity Y to quantity X. The sum linearly combines common influences before any quadrature uncertainty combination.

TABLE II
Traceability via BQ sensitivity coefficients.

BQ ID	SCL A	SCL B	SCL N
1	$c_{A,1}$		$c_{N,1}$
2	$c_{A,2}$	$c_{B,2}$	$c_{N,2}$
3		$c_{B,3}$	$c_{N,3}$
(4)			$c_{N,4}$

Since all measurements trace to independent BQs, the GUM's Welch-Satterthwaite equation works without compromise for expanded-uncertainty and measurement-decision-risk estimates. When potential BQs contain correlations, independent virtual BQs replace them, via either Cholesky [15] or singular-value [12] decomposition, a difference that changes storage and calculation details–see [12], [14]–[16]. Global use would require globally unique IDs and therefore a registry for common BQs, e.g., uncertain constants and functions.

B. Extensions

The above schema compactly represents full traceability data for complete uncertainty estimation. The schema does not require intermediate results storage; retaining data from the most recent calibration and the base quantities suffices. An option to include the intermediate data, however, would provide redundancy for quality verification and opportunities for refinement. Encoding upstream measurement functions (see Section IV-C) would do likewise. Finally, the given schema primarily implements only one uncertainty propagation method. Certificates might easily include a "case" or "switch" data element to indicate substitute schemas, e.g., for Monte Carlo methods. Such extensions would help satisfy the GUM's previously mentioned data-completeness admonitions.

While actual implementation details may differ, the framework presented here shows how simply machines may generate, propagate, exchange and process complete traceability data. Such a strategy would comply with the GUM's advice "to err on the side of providing too much information" while incurring negligible cost to information producers and consumers. A extensible data structure facilitates minimum viable products while retaining power for future applications.

IV. Modeling

We apply data completeness to measurement models. We wish to digitally capture information that current practice omits from analog documents. This applies to each MII document—accreditation scopes, instrument specifications and calibration certificates—so we take each in turn.

A. Accreditation Statements

A capability statement (accredited or not) advertises a laboratory's CMC uncertainties by measured quantity (perhaps under instrument type). In the general case, a CMC uncertainty varies with the desired quantity value, q_{cmc}, and any influence or input quantity values, designated here as vectors $\boldsymbol{q}_{\mathrm{inf}}$ and $\boldsymbol{q}_{\mathrm{inp}}$, respectively. An alternating-current amplitude CMC, e.g., usually depends on both desired amplitude and frequency (an influence quantity). Evaluating a CMC uncertainty digitally therefore requires data for variable uncertainty calculation.

Reviewing analog SoAs reveals CMC cases like Table III's examples. These cases all fall into step or ramp functions of the form $u_{\mathrm{cmc}} = c_1 q_{\mathrm{cmc}} + c_0$, where one constant may equal zero. If these cases covered all CMCs, storing the two constants in defined-purpose data fields would suffice for intelligent laboratory capability search and comparison, propagating CMCs into calibration uncertainties to prevent violating the accreditation, and other purposes.

TABLE III
EXAMPLE SOA EXCERPT

Measurand	Range	Uncertainty
Frost- or Dew-Point Temperature	−70 °C to 20 °C	0.10 °C
DC Voltage	0 mV to 200 mV	$0.3\,\mu\mathrm{V\,V^{-1}}$
Gage Length	0 cm to 36 cm	$160\,\mathrm{nm} + 8\,\mu\mathrm{m\,m^{-1}}$

However, exceptions to step and ramp CMC uncertainty functions no doubt already exist on SoAs. Furthermore, delving deeper exposes these simple CMC uncertainty expressions as conservative approximations for human consumption via analog documents. From the GUM methods [10] we should expect a non-linear form no simpler than

$$u_{\mathrm{cmc}} = \sqrt{c_1 {q_{\mathrm{cmc}}}^2 + c_0}, \tag{1}$$

which combines all uncertainty contributors into a variable term dependent on q_{cmc} and a fixed independent term. Fig. 2 compares (1) to its step and ramp simplifications. The gap between a published and actual CMC represents lost value that digitalization should recover: over- and understated uncertainties pose market risk and cost. With only analog documents, we accept small losses when the simplifications sufficiently reduce labor costs related to producing and interpreting the CMCs. But under digital transformation those labor costs evaporate and we should expect higher fidelity information.

We expect much more complex functions than (1) to accurately characterize some CMC uncertainties and so propose that SoAs feature an arbitrary CMC uncertainty function

$$u_{\mathrm{cmc}} = f_{\mathrm{cmc}}\left(q_{\mathrm{cmc}}, \boldsymbol{q}_{\mathrm{inp}}, \boldsymbol{q}_{\mathrm{inf}}\right), \tag{2}$$

which implicitly includes the CMC uncertainty's dependence on the quantity values and other factors. To include cases which require implicit numeric solutions, we would instead design CMC data elements to encode the model

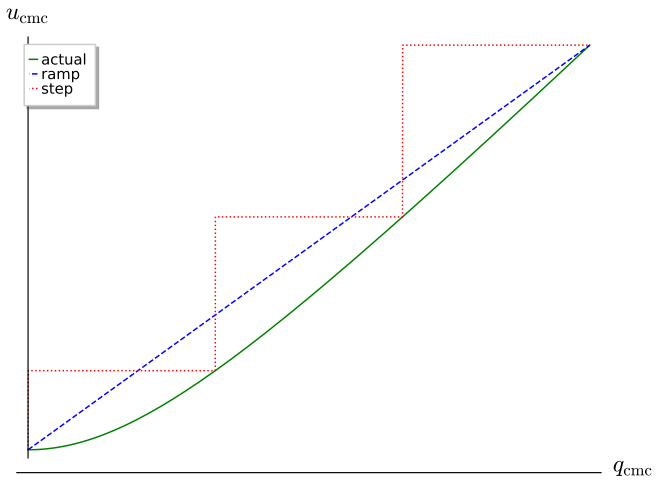

Fig. 2. Example CMC uncertainty functions over a range. Conservative step and ramp simplifications discard information and value.

$$h_{\mathrm{cmc}}\left(u_{\mathrm{cmc}}, q_{\mathrm{cmc}}, \boldsymbol{q}_{\mathrm{inp}}, \boldsymbol{q}_{\mathrm{inf}}\right) = 0. \tag{3}$$

Intelligent CMC optimization and utilization alone argue for arbitrary model evaluation functionality in MII documents, but let us examine the case for other documents.

B. Instrument Specifications

Among other things, instrument specifications provide MPEs for performance verification. Note that all our arguments for calculable CMC models apply also to MPEs: Like CMC uncertainties, an MPE, ϵ_{mp}, varies in general with the quantity values concerned $\left(q, \boldsymbol{q}_{\mathrm{inp}}, \boldsymbol{q}_{\mathrm{inf}}\right)$. Analog specification documents also conservatively simplify MPEs for human consumption as step and ramp functions, though infamously footnoted exceptions occur. Digital MPE data would facilitate intelligent instrument capability search and comparison, automatic calibration and verification, calibration interval analysis, etc. Finally, manufacturers and users lose value with overly conservative MPEs. Therefore, we propose that instrument specifications encode the arbitrary machine-calculable MPE functions (4) or models (5)

$$\epsilon_{\mathrm{mp}} = f_{\mathrm{mpe}}\left(q, \boldsymbol{q}_{\mathrm{inp}}, \boldsymbol{q}_{\mathrm{inf}}\right), \tag{4}$$

$$h_{\mathrm{mpe}}\left(\epsilon_{\mathrm{mp}}, q, \boldsymbol{q}_{\mathrm{inp}}, \boldsymbol{q}_{\mathrm{inf}}\right) = 0. \tag{5}$$

Specifications might model more than MPEs. Modeling instrument behavior mathematically [12], [17] allows predicting performance over the instrument's entire measurement space from a finite calibration-point set. Extant examples include ITS-90 range and subrange functions for platinum resistance thermometers and quadratic or cubic curve fits for force transducers. Essentially, the model serves as an instrument-wide calibration or correction function: Given any instrument indication q in the calibrated space, the related independent quantities, and model parameters $\boldsymbol{\theta}$, the function produces a

corrected measurement result q_c or, equivalently, an uncertain error relative to the indication. From MPE (4-5), we have the correction function (6) and general instrument model (7)

$$q_\mathrm{c} = f_c\left(q, \boldsymbol{q}_\mathrm{inp}, \boldsymbol{q}_\mathrm{inf}, \boldsymbol{\theta}, t\right), \tag{6}$$

$$h_c\left(q_\mathrm{c}, q, \boldsymbol{q}_\mathrm{inp}, \boldsymbol{q}_\mathrm{inf}, \boldsymbol{\theta}, t\right) = 0, \tag{7}$$

in which we have included time t to recognize that instrument measurement uncertainty grows after calibration [18]. A time-independent model would suffice for calibrating the instrument, but since uncertainty growth affects its use, the instrument model would ideally include time [12]. A time-dependent model would also allow automatic calibration interval determination and adjustment.

As an example, a linear resistance range independent of other instrument functions would have $q_\mathrm{c} = q\theta_1 + \theta_0$ with nominal parameters $\boldsymbol{\theta}_\mathrm{nom} = \left(1\,\Omega\,\Omega^{-1}, 0\,\mu\Omega\right)$. A length standard might have $q_\mathrm{c} = \Big((T-\theta_0)^2\theta_2 + (T-\theta_0)\theta_1 + 1\Big)q$, with reference temperature and expansion coefficients $\boldsymbol{\theta}_\mathrm{nom} = (T_\mathrm{o},\, \alpha_\mathrm{nom},\, \beta_\mathrm{nom})$ and time-of-use gage temperature as an variable input quantity $\boldsymbol{q}_\mathrm{inp} = (T)$. Multifunction instruments would have a model for each measurand, sharing or partitioning a single parameter set, depending on functional interdependencies. A vector of the individual models would model the entire instrument behavior [12].

Digital specification documents that contained model functions and nominal parameter values would form a digital-twin template for use with actual instruments associated with the document and design-time system evaluations. Furthermore, these embedded models lead us to calibration certificates.

C. Certificates

Calibration relates indications to measurement results [9]. Given that purpose, an MII calibration process would consume the instrument under test's model (6-7) and use the calibration data to calculate the model parameters $\boldsymbol{\theta}$, typically via curve fits. The model becomes the instrument's calibration function, transferred to the customer calibration certificate with the new parameter values. In so doing, the calibration process would utilize the already parameterized models from the measurement standards' certificates and perhaps also draw from the laboratory's CMC uncertainty model (2-3). See Fig. 3. When using the calibrated instrument, the customer's MII-aware system would likewise consume the certificate's calibration function, matching the model's free quantities to those in the customer processes to correct bias.

These bias-corrected measurement results would seamlessly improve downstream calibration and test results. "Smart" instruments (with on-board computing) might incorporate such features themselves [19], in which case the certificate's stored function may have nominal or near-nominal parameter values, or the instrument might store and communicate its own specification and certificate.

Such a calibration-process digital transformation may have further beneficial consequences. Except when adjustable parameters fall outside the modeling range or instrument functionality, seamlessly computed bias corrections would reduce the calibrate-adjust-calibrate-report paradigm to calibrate, report. Also, by VIM [9] definitions, many laboratories *verify* rather than *calibrate* some measurement standards and consequently derive traceability uncertainty from the specifications [20]. This method costs less than bias-correcting all measurements manually. A machine-driven calibrate-report paradigm (with uncertainty growth models) would obviate this traceability detour.

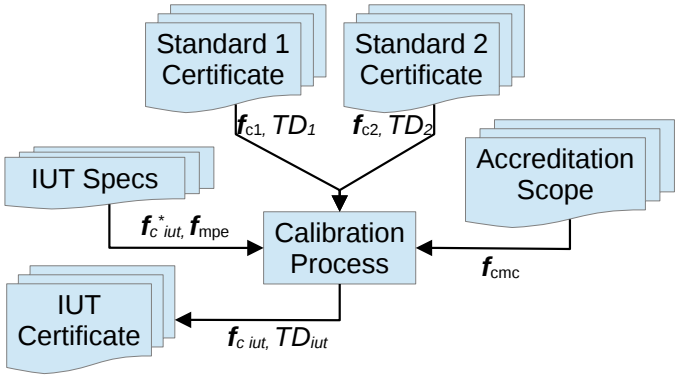

Fig. 3. A microeconomic measurement data flow within the macroeconomic IQI. IUT = instrument under test, TD = traceability data. The calibration process consumes the measurement standards' calibration functions and TD, the SoA's CMC uncertainty function, the IUT's MPE function and uncalibrated* correction model, sets the IUT correction function's parameter values from the calibration data, and stores the resulting IUT's calibration function and TD in the IUT certificate. A similar synergy would play into creating an SoA or specification document.

Section III-B mentioned extending traceability data with upstream measurement functions. This would amount to associating further instances of measurement models (6-7), with or without instrument parameters, with each measurement result. Downstream entities might use this feature as a redundant quality check to verify certified results, refine uncertainty estimates via another method, etc.

D. Implementation

Embedding calculable arbitrary mathematical models in digital documents requires a data structure. The structure should encode the mathematical expressions, identify quantity and parameter symbols, and record any known values [17], [21]. Crucially, to unambiguously connect measurement-process quantities with the correct free-variables, the structure should identify quantities with metadata from a standard taxonomy [1]. Providing for intermediate variables [17], [21] would facilitate multi-step, modular solutions for interdependent multifunction measuring-system models.

These requirements do not involve any new technology. As one example, the WC3 XML extension MathML [22] has established itself well and suits the current trend toward XML digital document formats. It also supports measurement units, though other unit solutions may arise.

V. User Interface

Of course, digital transformations should not ignore people. People will likely still oversee operations and make business and technical decisions, so systems should retain transparency and methods to present easily digested information. If desired, static document views (paper, PDF) may render the more complex equations with computed results or substitute graphic visualizations. Live views, though, will become more prevalent. These may interact with users and display information optimally, based on user parameter and configuration choices, e.g., plotting two competing labs' CMCs or instruments' MPEs together. Only ingenuity limits the options.

VI. Conclusion

Metrological data completeness together with MII-aware software would automate an interoperable IoT and the IQI in general. The enhancements beyond simply digitalizing current practice would add new value and reduce costs for downstream measurement-information consumers and upstream producers. At a minimum, data completeness would permit the following in metrology's digital transformation:

- Optimized CMC and MPE statements
- Intelligent laboratory capability search and comparison
- Intelligent instrument capability search and comparison
- CMC-informed and restrained uncertainty calculation
- Automatic instrument verification & interval assignment
- Transparent instrument adjustment and bias correction
- Full measurement-space uncertainty & MQM prediction
- Complete SI-traceability chain for every measurement
- Less frequent instrument adjustment
- More full calibrations and fewer verifications

We therefore conclude that digital metrological-document designs should include features to robustly and rigorously retain all available measurement information.

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