A Guide to Standardizing Digital Calibration and Measurement Capabilities

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Abstract: Demand for transparent digital measurement data exchange and processing continues to grow in the metrology industry. Automated data processing, however, requires metadata to adequately describe and identify the information content. In metrology, the measurand description comprises the fundamental metadata that associates meaning with measurement data.

Measurement information exists in many metrological documents, including calibration certificates and instrument specifications, but in the international quality infrastructure (IQI), CMC[1] descriptions define all approved and accredited measurands. These CMCs appear at the IQI's apex in the BIPM[2] KCDB[3] and throughout the IQI in official accreditation scopes and unaccredited measurement capability statements.

In the current state of the art, metrology experts develop CMCs primarily as free-form text that often lacks full information, requires subject-matter experts to interpret correctly, hinders machine processing, and does not lend itself to contextual or semantic search on CMC technical characteristics of interest: uncertainty, range, or even the specific measurand. This paper describes a measurand taxonomy structure suitable for use as CMC metadata and provides a procedure and examples for developing the metadata taxons to standardize CMCs in human- and machine-readable formats.

Learning Objectives

By participating in the session and using this paper, attendees will learn to

1. state the importance of a rigorously defined CMC structure,
2. relate how to develop fully defined CMCs, and
3. explain some benefits of digitally transforming metrology.

1. Introduction

In this paper we attempt to guide CMC development with an eye to producing unambiguous and complete CMC measurand descriptions suitable for automated machine processing and not dependent on human interpretation. The process revolves around standardizing a measurand data structure (schema) and an extensible list of measurands (taxonomy).

[1] calibration and measurement capability
[2] Bureau International des Poids et Mesures (International Bureau of Weights and Measures)
[3] Key Comparison Database

We intend the paper to serve as a multiple-purpose resource. First, the NCSLI's MII[4] initiative [1] to develop digital metrology documents (accreditation statements, instrument specifications and calibration certificates) requires structured measurement data formats and standardized measurand metadata, so the paper's content will inform the NCSL International 141 MII and Automation Committee's work. Secondly, after further refinement, the paper's content will aid in developing an MII specification document, such as an NCSLI Recommended Practice, which in turn will guide MII-aware software development such as the accreditation-scope editor [2] currently under development. Thirdly, the paper should support future CMC- and SoA-development training courses. Finally, we hope that the principles herein will help metrologists clarify CMCs on traditional SoAs and specifications for measuring instruments. We should note that while these instructions may facilitate developing SoA content, they do not at all intend to dictate traditional accreditation scopes' appearance, formatting, nomenclature, or content; the MII vision includes rendering traditional documents in any desired format from the underlying digital document.

Organization: Section 2 motivates the paper in the context of metrology's ongoing digital transformation and Section 3 describes the proposed measurand schema and taxon format. Section 4 takes the role of a metrologist drafting a measurand taxon, applies the schema and provides CMC-writing instructions while developing a new CMC as an example. Finally, Section 5 concludes the paper.

2. Metrology's Digital Transformation

In a world of interconnected *everything*, from factory sensors to tagged shipping containers to biometric devices on your person to self-driving cars, many industries have begun a digital transformation—digitally storing, transmitting, and leveraging data to enhance or create products and services and replace physical artifacts or optimize their utilization.

NCSLI's own MII initiative envisions a set of normative standards that define data structures, taxonomies, service protocols and security for locating, communicating and sharing measurement information seamlessly among our computing systems with little to no manual intervention. This replaces physical artifacts (paper documents) with enhanced digital equivalents and, as in industries already realizing the benefits therefrom, will save labor and spur new metrological products and services.

For CMCs in particular, we recognize that even for experts, many CMCs require clarification to interpret. That might mean calling the laboratory or reviewing many similar CMCs, which wastes time over and above the time spent producing, handling, and transcribing analog documents. For that reason, the NCSL International 141 MII and Automation Committee has developed [3, 4] and enhanced [2] a schema for digitally representing CMCs in a clear and consistent format. Besides all the supporting information required to unambiguously specify a CMC, the format utilizes an extensible taxonomy of unique quantity names, which the committee has drafted for the most commonly encountered CMCs.

The individual CMC taxons, or quantity name tags, will extend to MII instrument specification documents and calibration certificates. So, if a CMC named `Measure.Voltage.DC`

[4]Measurement Information Infrastructure

appears in a laboratory's SoA, then the laboratory might implement that CMC using an instrument whose digital specification would associate the same taxon with the function(s) and range(s) supporting that CMC in the laboratory's calibration process. Automation would then automatically match customers' instrument specifications labeled `Source.Voltage.DC` to the laboratory's CMC. The resulting MII calibration certificate would then tag the corresponding measurement results with `Source.Voltage.DC`. Both the instrument specification and the calibration certificate would have additional instrument-specific qualifying elements to disambiguate connectors, state, functions, ranges, etc., e.g., `RearOutput DCCoupled`, `HighImpedance`, `10VRange`, but those details falls outside this paper's scope. This metadata strategy links measurement information in all MII documents in a machine-readable fashion.

3. MII Measurand Structure

From its schema and taxonomy work, the NCSL International 141 MII and Automation Committee has begun drafting an MII specification from which we take material for this section and develop it further for refining the MII specification document. We first discuss quantity names for measurands and then the full measurand schema.

3.1. Measurand Name

Simply stated, the measurand identifies what we intend to measure [5]. A measurement will fit its purpose to the degree that the measurand specification unambiguously and accurately describes the intent. Likewise, locating and selecting the correct measuring instrument to perform a measurement or a laboratory with the appropriate CMC to calibrate the instrument depends heavily on measurand specification's clarity and completeness. This certainly applies to manual operations aided by human judgment, but becomes all the more critical for unaided machine interpretation.

For clarity, the measurand name, the measurand's output quantity, matters most. Therefore, MII documents tag their machine-readable MII measurands with clear, unique, and fully descriptive taxons from a defined measurand taxonomy. The individual MII taxons adhere to the following structure and naming rules adapted from [6]:

1. Every MII document identifies a given measurand by the same unique taxon string.
2. Each taxon may have aliases, such as commonly used equivalents (from *ISO-IEC 80000* [7], the KCDB, an AB's[5] conventions, etc.). These aliases may appear in human-readable documents generated from the digital document as the user prefers.
3. Each taxon comprises a series of tokens separated by the period (.) character.
4. Each token uses the UpperCamelCase[6] naming convention, e.g., `FrequencyModulation`.
5. A taxon's first token represents the process type, taking either the value `Measure` or `Source` to identify an input- or output-quantity measurement, respectively.[7]

[5] accreditation body

[6] also known as Pascal or Capitalized

[7] Regardless of whether the measurement process uses a direct, common source, or comparator measure-

6. The taxon's remaining tokens indicate the measured quantity.
7. The measured quantity's first token identifies the quantity kind [5], which shall have an entry in the MII quantity register.
8. Any further tokens after the quantity-kind token hierarchically qualify the quantity, proceeding from more general toward more specific quantity descriptors.
9. The string data format encourages concise tokens and widely recognized acronyms, e.g., `DC`, `RF`, `PRT`, `CMM`.
10. Parameters substitute for additional tokens to distinguish details within the same measurement process. `Source.Temperature.Simulated.Thermocouple`, for example, covers all thermocouple types via a type parameter, whereas a separate taxon (`Source.Temperature.Simulated.PRT`) covers platinum resistance thermometers (PRTs) because the measurement process changes (sourcing resistance instead of voltage).
11. Special tokens with their own syntax identify common measurement scenarios.
    (a) The `Ratio` quantity token precedes the quantity-kind token to identify a quotient of two like-kind quantities.
    (b) The `Coefficient` quantity token precedes two successive and differing quantity-kind tokens to identify a quotient of two unlike quantity kinds.
    (c) The `Delta` token follows the quantity(ies) to identify a further quantity that differs when measuring the quotient's numerator and denominator.
    (d) The `Model` token after a quantity introduces a standard instrument model.

Table 1 lists some taxonomy examples and their KCDB equivalents that illustrate the MII measurand structure and typical qualifier detail. Note that the taxon *as a whole* serves as a metadata tag to identify MII measurands. Other than distinguishing `Measure` or `Source` processes, a taxon's syntax and individual tokens do not encode meaning for machine processing; the taxon structure simply facilitates and standardizes taxonomy construction and organization.

MII Taxon	**Closest KCDB Alias**
`Measure.MassDensity.Solid`[a]	Density of solid
`Measure.Pressure.Pneumatic.Absolute.Static`	Absolute pressure, Gas medium
`Source.Current.AC.Sinewave.3Phase`	AC Current, Meters
`Source.Mass.Conventional`[b]	—

[a]Mass, as against flux or other densities; solid as against gas or liquid
[b]As against (true) mass

Table 1. Taxon examples [6].

ment method [8]. A token to capture both options might seem useful, but source and measure uncertainties usually, if not always, differ and therefore require separate CMCs.

3.2. Special Tokens

To aid in naming taxons, the MII measurand taxonomy treats two common quantities specially: ratios and coefficients. The term "ratio" indicates a dimensionless quotient [7], such as strain (length per length), amplifier voltage gain (voltage per voltage), or refraction index (light speed per light speed). "Coefficient" on the other hand, indicates a quotient of two different quantities [7], such as a transducer calibration correction (voltage per pressure). A ratio takes the name "factor" when used as a dimensionless proportionality constant [7]. In practice, some common measurand names ignore this convention, e.g., "reflection coefficient", "index of reflection", both of which we compute as ratios and use as factors. Both ratios and coefficients play into CMCs.

3.2.1. Ratios

We structure ratio taxons as `...Ratio.Q`[8], where `Q` names both ratioed quantities. `Q`'s structure follows the taxon rules—first a token for the quantity kind from the quantity register, then successively more specific descriptors. So, `Measure.Ratio.Pressure...` would identify a ratio of two particular pressures and `Source.Ratio.Power.RF...` would represent a ratio of two microwave powers. The quantity register would have entries for `Pressure` and `Power`.

3.2.2. Coefficients

Coefficients relate an instrument's input and output quantities. Unconditioned piezoelectric accelerometers, for example, output an electric charge that varies with sensed acceleration, a response requiring quantification. Manufacturers therefore specify a nominal coefficient value that users wish to calibrate in order to correct the transducer output, and so we want a CMC to describe a laboratory's compatible service. The MII taxon structure therefore includes the syntax `Measure.Coefficient.QOut.QIn...`, where the two quantities listed after `Coefficient` have quantity-register entries and the coefficient equals $Q_{\text{out}}/Q_{\text{in}}$. Accelerometer sensitivity would look like `Measure.Coefficient.Charge.Acceleration...`. When the two quantities require different descriptor tokens, the numerator's descriptor tokens appear directly after the two quantity names, and the denominator's descriptor tokens thereafter. So we would name a coefficient of DC voltage to absolute pressure `Measure.Coefficient.Voltage.Pressure.DC.Absolute`.

3.2.3. Delta

The two quantities involved in ratios and coefficients often have an influence quantity that differs between them. For example, we might measure a frequency response by first measuring an signal amplitude V_{ref} at a reference frequency, then changing the frequency and measuring the new amplitude V. The ratio quantity (V/V_{ref}) represents the frequency response between the two frequencies. After the main quantity, the special tokens `...Delta.QInf` flags an influence quantity `QInf` (with a quantity-register entry) that changes during the measurement. So using AC RMS amplitudes in this example, we would name their ratio `Ratio.Voltage.AC.RMS.Delta.Frequency`.

3.2.4. Instrument Models

So far, we've discussed ratios and coefficients only in a point-measurement context—calibrating a device at one or more measurement points and determining a *separate* bias-correction co-

[8] used for both ratios and factors since both require only one quantity kind

efficient value at each point. Coefficients also arise in a separate but related context though: the coefficients of a mathematical model (function) that corrects instrument indications *over a range*. Examples include ITS-90[9] range and subrange functions for PRTs, quadratic or cubic curve fits for force transducers, Callendar-Van Dusen (CVD) equations for RTDs[10], and many others. In theory, we may assign any measuring instrument a correction model and determine the model's coefficients from measurement results. Whether done at the calibration-point level or at the range, function, or instrument level, such a correction function with coefficient values raises the service from verification (that the instrument meets tolerances) to true calibration [5].

Though either the calibrating laboratory or the customer may have software to calculate modeling coefficients from the point-by-point calibration results, the laboratory more likely has the expertise, and for smart instruments, customers may prefer turnkey calibrations that load coefficients into the instrument. This might drive CMC taxons for identifying such measurement services. The MII tokens `...Model.M` would serve this purpose, where `Model` signals an immediately following defined model type `M`. So if an instrument's instrument specification tagged a measuring function with `Measure.Temperature.PRT.Model.ITS90`, then `Source.Temperature.PRT.Model.ITS90` would identify the CMC to calibrate that function. In general though, the MII instrument specification schema will provide for calibration models of any form for which calibration services may assign coefficient values for smart instruments and digital calibration certificates [9].

The following BNF[11] grammar defines the measurand taxon syntax

Taxon	::=	ProcessType . (Quantity | Ratio | Coefficient) [. Model]
ProcessType	::=	`Measure` | `Source`
Quantity	::=	RQK (. Descriptor)*
RQK	::=	<any name in the quantity kind registry>
Descriptor	::=	<any measurand-qualifying term>
Ratio	::=	`Ratio` . Quantity
Coefficient	::=	`Coefficient` . RQK_n . RQK_d (. $Descriptor_n$)* (. $Descriptor_d$)*
Model	::=	`Model` . ModelName
ModelName	::=	<any instrument-model name>

where the subscripts "n" and "d" represent numerator and denominator, respectively, and RQK means registered quantity kind.

3.3. Supporting Information

The measurand name identifies the measurement and disambiguates it from other measurements but does not specify the (critical) process or capability details. Here we discuss the further measurand detail required to clarify a CMC.

[9] International Temperature Scale, 1990

[10] resistance temperature detectors (or devices)

[11] Backus-Naur form: "|" separates alternatives, "*" means zero or more consecutive instances, angle brackets enclose descriptive text, parentheses group tokens

3.3.1. Definition
Regardless of care taken in naming taxons, a clear, human-readable definition helps disambiguate one measurand from another. This helps the metrologist select the correct measurand from a list, for example, when building an SoA. Also, since new measurands continually arise with new technology or measurement techniques, we will never have a complete measurand taxonomy. A definition thus helps determine whether the measurand of interest appears in the taxonomy or requires a new entry. Finally, an extensible taxonomy exposes both its taxons and their definitions to change reflecting the current state of knowledge. For example, if we everyone only measured static pressure, then the taxon `Source.Pressure` and its definition would require changes to differentiate `Pressure.Static` and `Pressure.Dynamic` once a demand for dynamic-pressure measurement arose.

3.3.2. Parameters
Samuel Clemens popularized the phrase "lies, damned lies, and statistics", which implies that statistics misrepresent truth more than outright lies. People do misuse and misinterpret statistics, primarily from ignoring the prior assumptions, whether innocently, conveniently, or deliberately. If a probability equals p only under conditions (x, y, z), then we abuse the facts to quote the probability without stating the conditions. Similarly, we devalue calibration without fully knowing and stating the measurement conditions, the measurand's state. Specifying the measurand's full state restricts its *definitional* uncertainty [5], the range of (true) values that match the measurand; failing to do so may inflate definitional uncertainty beyond other uncertainty components, or even beyond the instrument MPE[12] specification, essentially making the calibration worthless. We should define our measurands such that definitional uncertainty remains insignificant relative to other uncertainty components and include those definitions as metadata in instrument specifications, calibration certificates and SoAs.

The measurand state includes input quantities, influence quantities, and instrument operating conditions. Input quantities affect the measured (calculated) value and usually the CMC uncertainty. Influence quantities do not affect the measured value's calculation but may affect the CMC uncertainty. Both input and influence quantities determine the measurand's state and thus affect the measurement result, so CMCs and their representative taxons should specify the applicable quantities. Examples include dew or frost point temperature in chilled-mirror relative-humidity measurements, frequency in AC measurements, acceleration in accelerometer sensitivity measurements, temperature in dimensional and many other measurements. For some measurands, a non-numeric property such as a thermocouple type (J, K, S, T, ...) may apply.

The MII measurand structure refers to these quantities and properties as "parameters" and defines both required and optional parameters. An automated CMC search, a CMC uncertainty calculation and the actual measurement will not all succeed without the required parameters' values. Required parameters usually include the primary measured (output) quantity. Optional parameters, however may remain uncontrolled, perhaps invoking a higher uncertainty, or defaulting to a specified (nominal) value. Taxons in the taxonomy catalog designate parameters as required or optional as seems most appropriate, but when used in a

[12] maximum permissible error

CMC, the laboratory will choose which parameters to require, which to make optional with default values such as a 50 Ω input impedance or a 20 °C reference temperature, and which to omit entirely as immaterial to the measurement process.

A complete instrument specification includes the (rated, limiting, and reference) operating conditions [5] for which its specifications apply. However, an MII measurand taxon's parameters include instrument operating conditions only when they overlap with laboratory capabilities. For instance, a voltage reference standard may require battery operation (at a minimum voltage) for specified accuracy, but this procedural detail does not distinguish one laboratory's capability from another. In contrast, some rated or reference operating conditions may limit influence quantity values to ranges that some laboratories may not achieve, such as a tight ambient-temperature tolerance. In some cases, the CMC uncertainty would reflect the relevant capability, but not for all instruments.

3.3.3. Measuring Intervals

The abstract measurand taxons in the taxonomy apply to any measured value, so the taxonomy itself does not include measuring intervals (ranges [5] or nominal values). Concrete instances such as CMCs, however, should specify the measuring intervals over which they apply. The MII SoA structure includes this element, which human-readable SoAs should show with every CMC[13]. Besides their contribution to CMC uncertainties, this allows intelligent searches for useful calibration services, whether a quantity at a single point or an entire instrument range interests us. This logic applies to not only the output quantity, but also all the input and influence quantities and operating conditions. Customers may choose to omit optional parameter values for CMC searches or calibration requests, but SoA CMCs should define ranges, if only single points, for all supported parameters. As with parameter defaults, all ranges represent nominal values in CMCs (and instrument specifications); measured values appear only in calibration certificates.

3.4. Interchangeable Quantities and Scales

Some quantities have multiple scales or derive in known ways from other quantities. For example, we may characterize a microwave reflection in terms of "reflection coefficient", "VSWR"[14], or "return loss" and we convert between them via defined equations. Also, some instruments (nominally) follow known models, such as thermocouples' voltage-temperature responses. Table 2 gives example values.

Search Quantity	**Equivalent(s)**
reflection coefficient: 0.10	VSWR: ≈ 1.2; return loss: 20.0 dB
thermocouple input temperature Δ: 10 °C	nominal type-K output voltage: ≈ 0.397 mV

Table 2. Equivalent quantities.

The question then arises whether CMCs should express multiple quantities or scales to facilitate searches. The short answer: no. If customers wish to search for a lab to calibrate a thermocouple over a certain temperature range, they likely will not care to search by the corresponding voltage range, even though they will want to calibrate the DC voltage measuring

[13] Caveat: Measuring intervals may not apply to SoAs outside the calibration field.
[14] voltage standing wave ratio

instrument used with the probe over that range. Software should handle such conversions where required. The same applies to the microwave-reflection example. Laboratories, however, may list multiple CMCs in their digital SoAs as they think useful. Customers may also specify calibration results in a particular format, but that pertains to calibration certificates, not CMCs.

To complete the picture, Figure 1 depicts the current draft MII taxonomy schema.

4. CMC Development Example

Let's work an example to illustrate developing an MII measurand and how that might lead to a clear CMC, even on the traditional SoA. We'll take air flow, a quantity the NCSL International 141 MII and Automation Committee hadn't tackled before, to actually expand the taxonomy. Also, since many variables play into air flow, it will illustrate more of the MII taxon nuances.

4.1. Name the Measurand

Assuming (critically) that we already understand the measurement or will learn enough along the way, we should first clearly and uniquely name the measurand. Since we want to link to an MII measurand taxon, we first look for names in the MII taxonomy tree [10, currently]. The MII SoA editor [2] provides current pick lists. We (of course) don't find an existing air-flow entry for this new taxon, and so start creating one from scratch. If we take our example laboratory process as calibrating air-flow meters and similar instruments, then we want a CMC that *sources* air flow. Following taxonomy rules 3, 4, 5 and 6 we first envision the taxon `Source.AirFlow`.

Observing rule 7 though, we check the MII quantity database [11, currently] and find no entry for AirFlow.[15] At this point we widen our research and find the following quantity names that seem to address our CMC:

- "fluid flow" from the KCDB (with further qualification as "gas flow" or "liquid flow" and species)
- "mass flow rate" and "volume flow rate" from *ISO-IEC 80000* [7]
- "[20/M05] Flow Rate" from NVLAP[16] mechanical accreditation area, plus "liquid flow" and "gas flow" [13]
- "FQ[17]: Gas flow rate", "FQ: Volume of flowing gases", and "FQ: Mass of flowing gases" from DAkkS[18] [14]

Looking at approved SoAs from various ABs, we additionally find

> "Mass Flow", "Liquid Flow", "Gas Flow", "Flow - Air", "Flow - Gas", "Flow - Liquid", "Flow - Gas (Air)", "Air/Nitrogen Flow", "Flow Rate by Volume", "Air

[15] This testbed database serves as a quantity and unit reference for MII projects. Ultimately, we expect an appropriate IQI organization will host definitive quantity and unit registers with unique IDs, names and other relevant information [12]. Other proposals also exist, but the SI itself has ambiguities [12] to address.

[16] National Voluntary Laboratory Accreditation Program, a North American AB

[17] fluid quantities

[18] Deutsche Akkreditierungstelle, a German AB

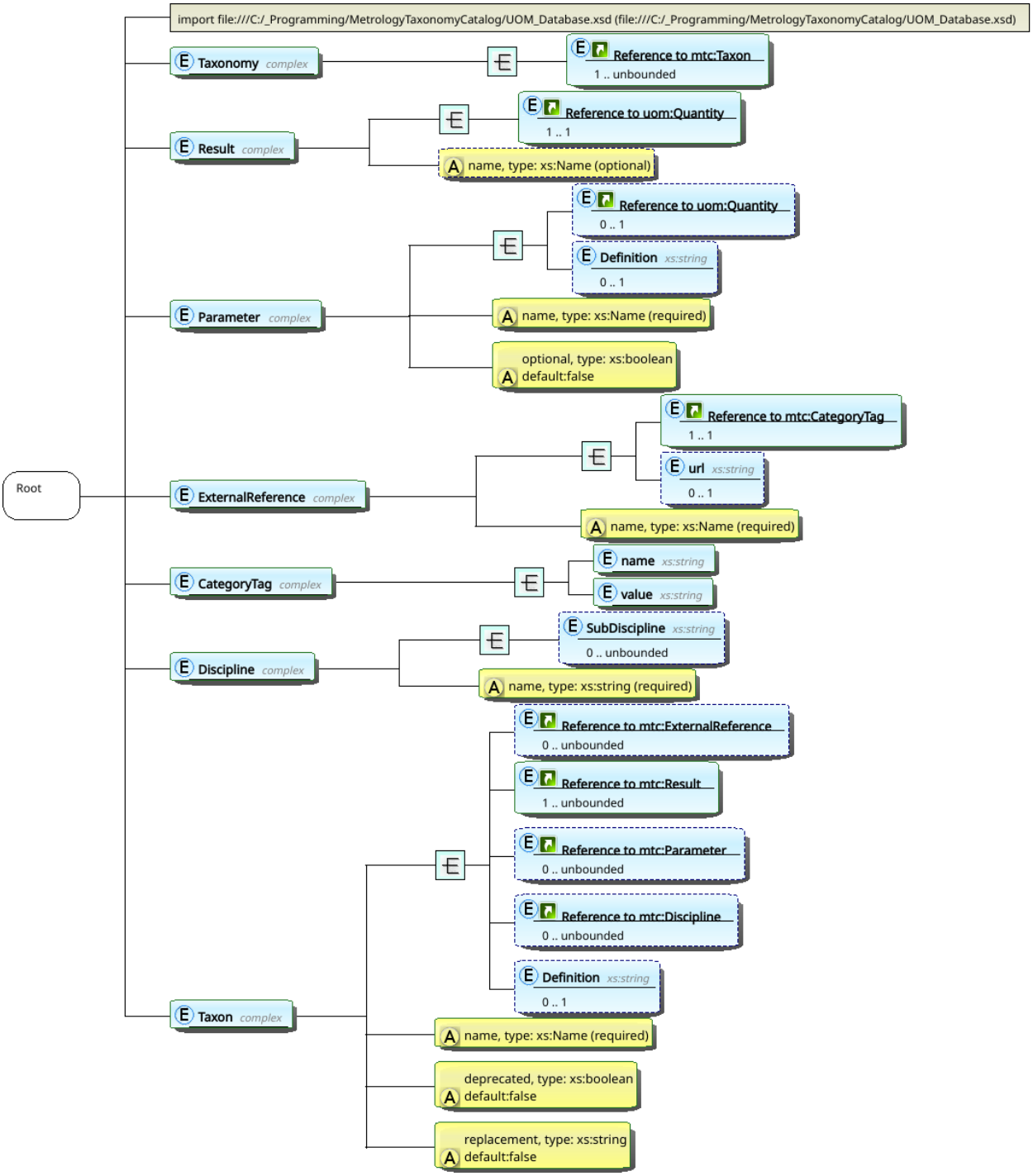

Figure 1. MII taxonomy schema (less the CMC-only elements). In addition to the elements previously discussed, the schema includes category and discipline tags to optionally map MII taxons to other nomenclature systems for human-readable output and interoperability.

> Volume Flow", "Flow Hydraulic", "Fuel Flow", "Flow Rate by Volume for Compressible Gas", "Volumetric Flow Rate (Water)", "Liquid Flow Rate Inline", "Liquid Flow Rate Non-Intrusive", "Gas Flow - Leak", "Gas Leak", "Gas Flow Rate Into Vacuum", "mole-flow-rate", "Flow Meter Factor", "Flow Calibration Factor", "Flow Meter", "Determination of Flow Meter" (by gas or liquid species), "Electrical Output of Flow & Pressure Devices",

plus many other categorizations by flow instrumentation. Never mind confusion factors such as immaterial quantities with similar names or measurement units like melt-flow index, flow velocity, air velocity, evaporation, and load rate. And to confound the uninitiated, units such as "sccm" (standard cubic centimeters per minute) sound like volume flow units but really refer to mass flow (via standardization to reference conditions).

The widely varying nomenclature in use brings home the fact that metrology lacks quantity-naming standardization and the difficulty automated systems (and humans!) have interpreting SoAs and other measurement information documents. However, once we settle on an MII taxon that situation will not confuse software interpreting a digital SoA. We've also learned we should distinguish liquid flow from gas flow and mass flow from volume flow, not to mention other flow types we stumbled on, like heat flow and sound-volume flow [7].

To organize these CMCs into a taxonomy tree, we look back to rule 7 and identify the quantity kinds involved. This boils down to mass flow, volume flow, ratios (flow meter factors) and coefficients (electrical output of flow devices)[19]. So, we'll use the existing special tokens 11a and 11b, and then, with a nod to [7] propose `MassFlowRate` and `VolumeFlowRate` as entries in the MII quantity list.

With further study, we realize that 1) mass flow covers leaks, 2) outlet pressure covers flowing into vacuum or otherwise, 3) fluids include gases and liquids but their measurement processes differ, 4) a species-type property would identify the fluid, if not quantity values like viscosity and compressibility, 5) we may have both inline and non-intrusive `Measure` processes, though the `Source` process seems the same for either. So after discarding the variant wordings, we draft this initial taxonomy tree branch:

- `Source.MassFlowRate.Gas`
- `Measure.MassFlowRate.Gas.Inline`
- `Measure.MassFlowRate.Gas.NonIntrusive`
- `...MassFlowRate.Liquid...`
- `Source.VolumeFlowRate.Gas`
- `Measure.VolumeFlowRate.Gas.Inline`
- `Measure.VolumeFlowRate.Gas.NonIntrusive`

[19] We ignored "mole-flow-rate" because our fictitious laboratory conveniently leaves customers to calculate it from mass or volume flow rate as desired, and we think the molar quantity kind will fit into the tree when desired.

- `...VolumeFlowRate.Liquid...`
- `Source.Ratio.MassFlowRate.Gas.MeterFactor`
- `Source.Coefficient.Voltage.MassFlowRate.DC.Gas`

To shorten the list, we've fully expanded only the taxons that immediately interest our laboratory (in blue), but have used rule 8 to organize the tree and left non-process-changing details to parameters per rule 10. We also envision measurands involving tokens 11a for flow correction factors and 11b to support instruments that output a DC voltage proportional to input air flow. The latter taxon respects rule 9. We may always add other taxons later as desired.

4.2. Define the Measurand

Next we should develop the measurands' supporting information. We'll use one of our fictional laboratory's CMCs, `Source.MassFlowRate.Gas`, for this example. As a draft measurand definition we expand [7]'s succinct mathematical definition ($q_m = dm/dt$) into

> This process sources a reference mass flow rate of gas for calibrating gas flow meters. The instantaneous mass flow rate q_m equals dm/dt, sometimes estimated as $\Delta m/\Delta t$ using the total mass Δm flowing through a defined space in time Δt.

4.3. Identify the Measurand's Parameters

Based on our gas-flow measurement knowledge, the following influence and input quantities affect measurement results: gas type (ambient air, nitrogen, CO_2, etc.), gas temperature and pressure, reference temperature, reference pressure, outlet pressure, and ambient temperature, pressure and relative humidity. It pays, however, to research further because the number of relevant quantities increases as you move up the traceability chain—in order to reduce uncertainties, higher-level laboratories account for more influences than lower-level laboratories. After reviewing some detailed manufacturer specifications, NMI-issued certificates, and key-comparison reports, we add Reynolds number, gas humidity, reference compressibility, gas velocity. We also decide to specify the point at which to measure the gas properties (inlet or outlet).

Next we determine which quantities and properties (parameters) the CMC requires and which ones we should leave optional. The customer may specify optional quantities to customize the service as desired, either to fit the application or reduce measurement uncertainty. To verify that our CMC covers a requested calibration and to determine the CMC uncertainty, we normally require the measurand's (output) quantity, though a laboratory may wish to default even it to a commonly used value, for example a 1 kg mass. For air flow though, we will set it as required.

Many flow-meter applications require a correction if measuring a gas other than the calibration medium, or perhaps a separate calibration for each medium. Assuming most users normally measure air, we make the gas type optional and default its property value to ambient air. Some instruments with mass-flow sensors, and all those converting a volumetric measurement to mass flow, require a gas-pressure-temperature correction. The volumetric instruments also require reference values. Unless specifying a "dry" gas, the correction also

involves the gas humidity. For higher accuracy, the gas compressibility requires a correction for pressure. We therefore default those optional parameters to our normal process values along with ambient laboratory conditions.

Customers rarely specify outlet pressure so we make it optional also. Reynolds number (Re), which characterizes the degree of laminar versus turbulent flow, affects meter indications and varies with flow rate, gas type and instrument configuration[20]. Calibrating a meter under turbulent flow when the customer uses it for laminar flow may cause significant error. To operate correctly, some flow meters require a minimum gas velocity, which also depends on the flow rate and measurement setup. We won't require customers to specify Re or gas velocity, but we should analyze our measurement processes to evaluate our capability ranges. Default values appear in the digital CMC, customized for our laboratory, but not in the measurand definition. This leads to our draft parameter list:

- **Required Parameters**
  - Mass flow rate
- **Optional Parameters**
  - Gas Type
  - Gas Temperature
  - Gas Pressure
  - Gas Relative Humidity
  - Gas Compressibility
  - Reference Temperature
  - Reference Pressure
  - Reference Relative Humidity
  - Reference Compressibility
  - Ambient Temperature
  - Ambient Pressure
  - Ambient Relative Humidity
  - Outlet Pressure
  - Reynolds Number
  - Gas Velocity

These parameters complete the taxon for the general case. Laboratories will include or omit these parameters as they see fit to refine their CMCs. The MII project intends to maintain extensible taxonomies and schemas, so if further research or technology advancement drives

[20] assuming the measurement setup doesn't limit it

additional parameters, we may add them to the taxon later. A presentation at this conference [2] will demonstrate a beta version of the MII Taxonomy and SoA editors that illustrate how domain-specific tooling will replace spreadsheets and word processors for this purpose in the future. Such tooling will streamline the CMC- and SoA-development process while producing clearer, more complete, and unambiguous documents.

4.4. Final Result and Human-Readable Translation

The measurand description and details will likely change after review by MII and flow-measurement experts, but the essential structure seems sound. So, assembling our draft work produces the following measurand for submission to the MII taxonomy:

Source.MassFlowRate.Gas

> This process sources a reference mass flow rate of gas for calibrating gas flow meters. The instantaneous mass flow rate q_m equals dm/dt, sometimes estimated as $\Delta m/\Delta t$ using the total mass Δm flowing through a defined space in time Δt.

- **Required Parameters**
  - Mass flow rate
- **Optional Parameters**
  - Gas Type
  - Gas Temperature
  - Gas Pressure
  - Gas Relative Humidity
  - Gas Compressibility
  - Reference Temperature
  - Reference Pressure
  - Reference Relative Humidity
  - Reference Compressibility
  - Ambient Temperature
  - Ambient Pressure
  - Ambient Relative Humidity
  - Outlet Pressure
  - Reynolds Number
  - Gas Velocity

Whether rendering a digital CMC in a live view or printing a conventional SoA, the user will want to see the CMC in a familiar format. Aliases play a role here (Rule 2). The human-readable version should preferably show familiar terms, e.g., “Relative Humidity” rather than

"Ratio.Humidity.Relative". Nevertheless, the rendered CMC should not omit important information such as "Measure" or "Source", whatever the terminology used, at least until digital transformation matures and spreads sufficiently to make traditional documents a mute point. Table 3 shows our measurand taxon as a full CMC (adding measuring intervals and a simple uncertainty) in a common human-readable SoA layout. An MII SoA, as generated from an SoA editor, would contain our data in digital form, rigorously encoded in an unambiguous data schema for machine processing.

Measurand	**Uncertainty**	**Comments**
Mass flow rate, 1 slpm to 1000 slpm Gas: ambient air, dry nitrogen Gas Temperature (inlet): 23 °C Gas Pressure (inlet): 800 kPa 100 kPa to 1000 kPa Gas Relative Humidity: 45 % Reference Temperature: 20 °C Reference Pressure: 101.325 kPa Reference Relative Humidity: 36 % Reference Compressibility: 0.9997 Ambient Temperature: 23 °C Ambient Pressure: 800 kPa Ambient Relative Humidity: 45 % Outlet Pressure: 0 psig 0.1 kPa to 800 kPa Reynolds Number: 1000 100 to 2000 Gas Velocity: 400 cm s^{-1} 1 cm s^{-1} to 800 cm s^{-1}	±0.3 % of reference value	Source for calibrating inline or non-intrusive flow meters
...	...	...

Table 3. Example CMC, human-readable. Default parameter values shown underlined. Parameter ranges shown as examples only and might not correspond to workable combinations. Uncertainty oversimplified for illustration.

We should note one important matter regarding CMC uncertainties in digital documents. True digital transformation does not limit itself to simply digitizing paper-based processes. We currently state CMC uncertainties (and instrument specification MPEs) in simplified forms (as in Table 3) suitable for manual creation, interpretation, and use. The real uncertainty evaluations take complex forms over the parameter ranges and we lose value when approximating them with conservative CMC statements [9]. To that end, digital documents will have schema to accurately encode arbitrary mathematical functions to represent CMC uncertainties, among many other quantities [9]. For SoAs this means a single uncertainty entry would suffice for some CMCs rather than breaking it up by ranges.

5. Conclusion

In this paper we have detailed the MII measurand structure for CMCs as currently envisioned and embedded in the MII accreditation scope schema. We illustrated a process for drafting a new MII measurand for submission to the MII taxonomy and how that leads to more clear and complete CMCs. In the future, we expect an MII Taxonomy Editor will facilitate this task and MII SoA editors will use the MII taxonomy to generate unambiguous accreditation scopes that machines and humans may use with confidence. The NCSL International 141 MII and Automation Committee would like to collaborate with measurement-area experts and CMC developers in laboratories and ABs to refine the SoA and taxonomy editors and the MII taxonomy itself.

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