Digital Transformation in Metrology Workshop
Digital metrology: what does it mean and how to plan for it?

Mark Kuster, mjk@ieee.org

Independent Researcher, Consultant

Toward a measurement information infrastructure–leadership opportunities for ultimate success

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Section 1

Introduction

Digital metrology: what does it mean and how to plan for it?

Toward a measurement information infrastructure–leadership opportunities for ultimate success

Abstract: Metrologists have automated measurement processes for decades–data acquisition, report generation, etc.–but typically in isolation with little system-wide integration. In the early 2010s, NCSLI members began discussing ideas to overcome this fragmentation by developing protocols for exchanging data between metrology systems without human intervention. Since first publicizing these ideas a decade has passed. We have made both missteps and progress toward the goals. This talk will highlight the way forward and the crucial ways in which technical leadership will drive success.

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Today's topics

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1. Introduction
2. MII background

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3. Measurand taxonomy

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4. Key identifiers for metrology data

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5. Leadership roles

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5. Leadership roles
6. Conclusion and discussion

Acronyms

- NCSLI—NCSL International
- DX—digital transformation
- IQI—international quality infrastructure
- SoA—scope of accreditation
- DCC—(PTB's) digital calibration certificate
- KCDB—key comparison database
- FAIR—findable, accessible, interoperable, reusable
- CMC—calibration and measurement capability
- PID—persistent identifier
- HC—hybrid comparison
- M-Layer—metrology information layer to support measurement systems

MII (measurement information infrastructure)

set of normative standards that unambiguously define data structures, taxonomies, service protocols and security for locating, communicating and sharing measurement information

NCSL International

- Established 1960 in the United States, now international at `https://ncsli.org/`
- Volunteer-driven, measurement-science professional organization
- Annual conference every July or August
- Publications
  - Recommended practices
  - Laboratory management guides
  - Standards
  - Tutorials, webinars
  - *Metrologist* magazine
  - *Measure* journal

Section 2

MII background

NCSL International 141 MII and Automation Committee History

- 2013: Began thinking seriously about digitalizing metrology
- 2013: Started the "Toward a Measurement Information Infrastructure" column in *Metrologist*
- 2015: Rechartered the Automation Committee to focus on MII development
- 2015: Began an association with the Asia-Pacific Region at the biannual Australasian Measurement Conference
- 2015-2023: Development, proofs-of-concept, publications, collaboration and conferences
- 2023: NCSLI President Georgette McDonald signed the Joint Statement of Intent on DX
- For further information see `http://miiknowledge.wikidot.com/`

MII Products

- High-level unified data models for all measurement-data documents
- XML schema, editor and concept proofs for accreditation scopes
- M-Layer: fundamental digital representations for quantities, scales and units
  - Proposed to the CIPM Digital SI Expert Group
  - Prototype registry and API established
- Measurand metadata taxonomy for digital-document interoperability
  - Example: `Measure.Pressure.Pneumatic.Gage.Static`
  - BIPM would like the taxonomy linked to its service categories.
- GitHub repository established for collaboration
- Specification document and open licensing in progress
- We offer experience and lessons learned from ten+ years of work.

Problems and solutions

(I)nteroperability problem for machines

Digitalization problems have stymied past efforts by other organizations. Along the way, the MII group encountered some of these same issues.

(F)indable
(A)ccessible
(I)nteroperable—the most difficult!
(R)eusable

Solution

Committee members understood metrology and had past digital-systems experience and implementation success. They knew that existing technology would meet the challenges.

Web search, pub-sub systems
Open internet systems, persistent identifiers
Semantics and standards
Standard formats

Problems and solutions

(I)nteroperability problem for machines

Other organizations had given up on similar ideas, perceiving the problem as too complex from looking only at many different document instances and ignoring the bigger picture.

Solution

A unifying measurement-data model:

- unique identifers for all (R)eusable data;
- flexible quantity values (abs., relative, . . .);
- nominal, reference, measured values, . . .
- quantity-value intervals for
  - the quantity of interest;
  - influence and input quantities;
  - environmental and operating conditions;
- parameterized measurement models;
- MPEs as equations or scripts;
- renderable to humans as desired.

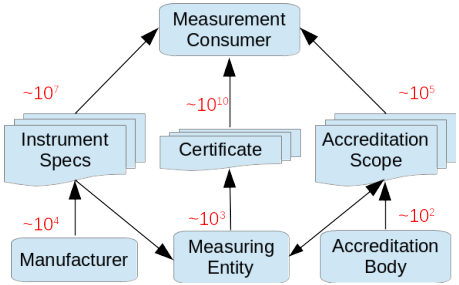
Problems and solutions

(I)nteroperability problem for machines

Still too many cases to consider: different documents, laboratories, ABs, manufacturers, ...

Solution

Start small with the statement of accreditation (SoA). The refined data model will then extend to other document types.



Problems and solutions

(I)nteroperability problem for machines

Measurement units do not suffice to identify measurements—not their job!, e.g.:

- 10°: optical incidence or phase angle?
- 1.2 N m: torque or energy?
- 10 g: gram or "standard" gravity (g)?
- 0.45 (1) Which of thousands of dimensionless quantities?

Free-form quantity descriptions do not solve the problem either.

Solution

Explicitly identify the measured quantity and associate units with quantities.

Quantity: Length
Associated units: m, in, ft, yd, ...

Quantity: Pressure
Associated units: Pa, mmHg, psi, bar, ...

Quantity: Temperature
Associated units: K, R, °C, ° F, ...

Problems and solutions

(I)nteroperability problem for machines

No standardization on terminology:

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

Solution

Create a database of unique quantity identifiers for machines.

Allow human-readable documents to substitute terminology as desired.

May vary by industry, organization, language, . . .

Problems and solutions

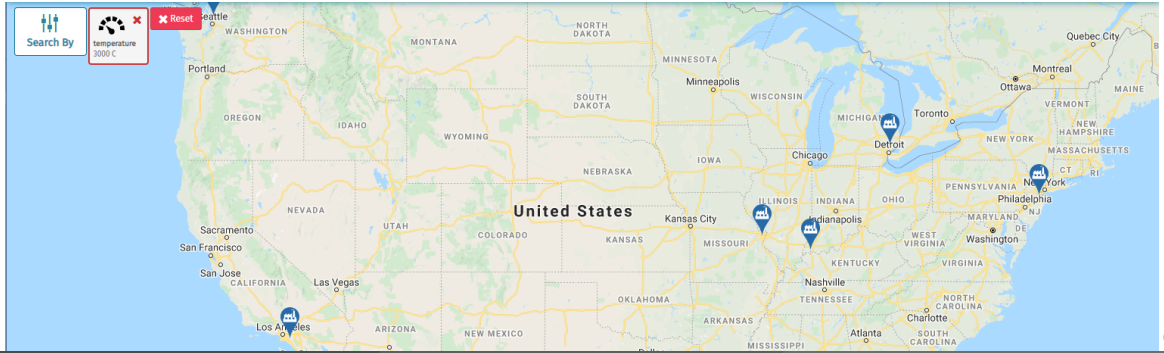
(I)nteroperability problem for machines

Insufficient context for machines to distinguish measurands of the same quantity. Measuring or sourcing? Instrument or sensor?

Solution

Uniquely identify measurands in a taxonomy.

`Source.Temperature.Simulated.Thermocouple`
`Measure.Temperature.Absolute`



Problems and solutions

(I)nteroperability problem for machines

A multitude of measurands:

- Many compound (quotient) quantities
  - Dimensionless correction factors
  - Sensor calibration coeffients
- Differential quantities
  - Oscilloscope scale linearity
- Pragmatic quantity equivalences
  - Actual and ITS-90 temperature
- New measurands as technology and applications expand

Solution

Abstract fundamental distinctions:

- Simplifying tokens
  - `Source.Ratio.MassFlowRate...`
  - `...Coefficient.Voltage.Strain...`
- Differential token
  - `Measure.Voltage...Delta.Voltage`
- Transformation token
  - `...Temperature.PRT.Model.ITS90`
- Extensible controlled taxonomy managed on GitHub

Problems and solutions

(I)nteroperability problem for machines

In practice, we measure a much more complex set of quantities than just SI quantities on ratio scales.

- Imperial, US Customary, regional. . . units
- Ratio, interval, cyclic (modular), ordinal, nominal. . . scales

Solution

Generalize the simple quantity ID database and unit conversions to M-Layer registries and PIDs.

- Generalize to any scale and unit system
- In short, go back to fundamentals and eliminate pragmatic shortcuts.

Section 3

Measurand taxonomy

Taxonomy construction

Analyze human terminology...
"Mass Flow", "Liquid Flow", "Gas Flow", "Flow - Air", "Flow - Gas", "Flow - Liquid", "Flow - Gas (Air)", "Air/Nitrogen Flow", "Flow Rate by Volume", "Air 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", ...

...and standardize it for machines.

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

"A Guide to Standardizing Digital Calibration and Measurement Capabilities", *Metrologist*, 15-2, 2022.

Draft taxons

Capacitance
Conductance
Conductivity
Current.AC
Current.AC.Noise.RMS
Current.AC.Sinewave
Current.AC.Sinewave.2Phase
Current.AC.Sinewave.3Phase
Current.AC.Squarewave
Current.AC.Trianglewave
Current.DC
Current.DC.Delta.Current.LoadEffect
Current.DC.Delta.Current.SourceEffect
Current.DC.OutputAndReadback
Density.Mass.Gas
Density.Mass.Liquid
Density.Mass.Solid
Energy.AC.Sinewave
Energy.AC.Sinewave.Simulated
Energy.AC.Sinewave.Simulated.2Phase
Energy.AC.Sinewave.Simulated.3Phase
Energy.DC
Energy.DC.Simulated
Force
Frequency
Frequency.AmplitudeModulation.Rate
Frequency.FrequencyModulation.Deviation
Frequency.FrequencyModulation.Rate
Frequency.PhaseModulation.Rate
Humidity.Absolute
Impedance
Inductance
Length
Length.Circumference
Length.Diameter
Length.Form.Flatness
Length.Form.Parallelism
Length.Form.Perpendicularity
Length.Form.Roughness
Length.Form.Roundness
Length.Form.Sphericity
Length.Form.Straightness.Axis
Length.Form.Straightness.Surface
Length.Radius
Mass.Apparent
Mass.Conventional
Mass.True
Phase.PhaseModulation
Phase.ReflectionFactor.RF
Phase.TransmissionFactor
PhaseNoise.SideBand
Power.AC.Sinewave
Power.AC.Sinewave.Simulated
Power.AC.Sinewave.Simulated.2Phase
Power.AC.Sinewave.Simulated.3Phase
Power.DC
Power.DC.Simulated
Power.RF.Sinewave
Pressure.Hydraulic.Static
Pressure.Pneumatic.Absolute.Static
Pressure.Pneumatic.Differential.Static
Pressure.Pneumatic.Gage.Static
Ratio.AmplitudeModulation
Ratio.AmplitudeModulation.Delta.Rate
Ratio.Density.Mass
Ratio.Distortion
Ratio.Distortion.AmplitudeModulation
Ratio.Distortion.FrequencyModulation
Ratio.Distortion.PhaseModulation
Ratio.DutyCycle
Ratio.FrequencyModulation.Delta.Rate
Ratio.Humidity.Relative
Ratio.Humidity.Specific
Ratio.PhaseModulation.Delta.Rate
Ratio.Power.ReflectionFactor.RF
Ratio.Power.RF.Sinewave.Delta.Frequency
Ratio.Power.RF.Sinewave.Delta.Power
Ratio.Power.RF.Sinewave.Harmonic
Ratio.Power.RF.Sinewave.Spur
Ratio.Power.TransmissionFactor
Ratio.PulseModulation.CWtoPulsedPower
Ratio.PulseModulation.OnOffPower
Ratio.Torque
Ratio.Voltage.AC.Ripple.OnDC

Draft Taxons

Ratio.Voltage.AC.Sinewave.Delta.Frequency
Ratio.Voltage.AC.Sinewave.Delta.Voltage
Resistance
Resistance.Insulation
Temperature
Temperature.Radiometric
Temperature.Simulated.PRT
Temperature.Simulated.RTD
Temperature.Simulated.Thermocouple
Time.Interval

Time.Period
Time.PulseWidth
Time.Transient
Time.Transition
Time.Transition.PulsedRF
Time.UTC
Torque
Torque.HydraulicPressure
Voltage.AC
Voltage.AC.NoisePeakToPeak
Voltage.AC.Ripple.OnDC

Voltage.AC.Sinewave
Voltage.AC.Sinewave.2Phase
Voltage.AC.Sinewave.3Phase
Voltage.AC.Squarewave
Voltage.AC.Trianglewave
Voltage.DC
Voltage.DC.Delta.Voltage.LoadEffect
Voltage.DC.Delta.Voltage.SourceEffect
Voltage.DC.OutputAndReadback
Voltage.DC.Segemented.Delta
Voltage.PeakToPeak

Solution: abstract taxon definitions customized for any context

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 (with ranges)**
  - Mass flow rate
- **Optional Parameters (with ranges)**
  - 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

Hybrid comparison examples

Think about the expertise required to properly specify the measurement and its uncertainty.

- DC Resistance of 10 k
  - `Source.Resistance`
  - resistor temperature (power < 0.1 W)
  - ambient temperature?
  - ambient humidity?
  - stabilization time?
- Gage-block central length
  - `Source.Length.GageBlock`
  - ambient temperature
  - ambient humidity?
  - CTE (material)
  - reference temperature
- Liquid in glass thermometer
  - `Measure.Temperature`
  - immersion depth
  - ambient temperature
  - ambient humidity?
- Helix angle
  - `Source.Angle.Helix`
  - ambient & reference temperatures
  - face width?
  - number of teeth?
  - pressure angle?
  - normal module?

Section 4

Key identifiers for metrology data

Identifiers and relations

Hybrid comparisons depend on DCCs, CMCs, instrument specifications,
which depend on measuring systems, instruments, organizations and all their components,
which depend on measurement data,
which depend on measurement specifications, capabilities, results, traceability,
which depend on measurands (MII taxonomy),
which depend on quantities, scales, unit systems, units (M-Layer).

DX requires persistent identifiers (PIDs) for all these elements.

Section 5

Leadership roles

Keys to Success

DX will solve the problem and foster innovation if

- fit-for-purpose and championed for adoption.

Simple digitization will not suffice. That only . . .

- changes the package, the wrapper,
- prolongs existing manual processes and weaknesses,
- retains ambiguity that foils machine consumption,
- leaves us with manual processing in a different form.

Critical Success Factors

True fit-for-purpose DX requires rethinking our processes to leverage digital technology.
For true DX we should:

- Rethink our processes from the ground up.
- Replace our manual shortcuts.
- Discard pragmatic practices for extensible replacements.
- Champion adoption within top-level authorities.

Top-level authorities have committed to DX.

- BIPM and OIML statements for World Metrology Day 2022 (paraphrasing):
  - This exciting digital technology will revolutionize our community.
  - It will enable open, transparent, human-readable, machine-actionable information exchange.
  - FAIR data principles: Findable, Accessible, Interoperable and Reusable
  - CIPM will develop an SI digital framework as fundamental support.
- Joint Signatories Statement of Intent on DX

Leaders and experts wanted!

DX will require a joint effort between experts & leaders. You here today have the expertise within your organizations.

Leaders

- provide top-level support,
- understand the big picture,
- direct digitization from a scientific viewpoint,
- delegate expert metrologists to liaison with other groups.

The fundamental DX pieces exist, so subject-matter experts may

- apply their metrological expertise to specific digitization issues,
- develop taxonomy subtrees,
- refine taxon parameter lists,
- in general, conceptualize and model metrology for DX.

Section 6

Conclusion and discussion

Acknowledgments

Many thanks to

- Asia-Pacific Metrology Program
- Blair Hall, APMP DXFG Chair
- Cherine Marie-Kuster
- Some images came from freepik.com.

And Thank You for your time!

Questions to consider

Each workshop discussion group should select and discuss one of the questions below.

1. What essential data do HC reports contain for DX?
2. How would you link the CMCs, instrument functions, and measurement results involved in a hybrid comparison?
3. How would you identify the relevant influence quantities to ensure a valid comparison?
4. Who within your group or technical committee would you delegate for taxonomy development?
5. What else will facilitate your DX success?