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IMPLEMENTING AN M-LAYER DATA MODEL

Mark Kuster [a,*]

[a]Independent Researcher and Consultant, Dumas, Texas, USA; https://orcid.org/0000-0001-5609-6812
[*]Corresponding author. E-mail address: mjk@ieee.org

Abstract – Recent work has proposed a metrology-information layer (M-Layer) to support digital systems with quantities and units by addressing the difficulties conventional quantity-unit systems pose for digitalization. This paper reports work toward developing the M-Layer's current abstract conceptualization into a concrete model, working prototype, and demonstration software, with the eventual goal to create a FAIR (findable, accessible, interoperable, reusable) resource.

Keywords: M-Layer, aspects, quantities, measurement units, measurement information infrastructure, digital metrology

1. INTRODUCTION

The international system of units and quantities [1, 2] and documents such as [3] define the basic references and nomenclature that supports most world measurements and quantitative specifications. This system, though not comprehensive, has served science and commerce well.

Metrology's digital transformation, as BIPM has recognized [4], requires a *digital* system of quantities and units. Simple digitization, however, does not suffice for digital transformation. To digitize, digitalize, and transform, metrology should rethink its practices from the ground up in order to identify and eliminate the suboptimum pragmatic elements that, if propagated into automated systems, undercut the full gains that digital transformation promises. Quantities and units lie at the ground level so we start there.

Digital quantity-unit systems face multiple realities—that if accounted for in the beginning will smooth and enhance digital transformation—including

1. both SI and non-SI measurement units,
2. exceptional measurement scales,
3. measurand ambiguity that challenges automated data consumption,
4. nonlinear unit conversions,
5. restricted operations by scale type.

In [5], the authors propose a metrology-information layer, an M-Layer, to standardize a universal digital system of quantities and units without altering the human systems in use. Conceptually, the M-Layer generalizes measurement "unit" (and the VIM's "reference" [6]) to "scale" and similarly generalizes "quantity" to "aspect" as denoted in [7].

The M-Layer would allow any measurement unit (reality 1) on any scale (reality 2), introduce an aspect identifier $\langle q \rangle$ to disambiguate quantities and facilitate machine-actionable (MA) documents (reality 3), provide for arbitrary conversion functions between scales (reality 4), and capture the meaningful operations among scales (reality 5). This generalization unites all digital measurement data under a single methodology. Without such innovations, metrology laboratories and other measurement producers and consumers will inevitably encounter measurements that require some ad hoc data in digital documents that their customers' software may or may not consume automatically, not to mention the rest of the world.

Subsequent work [8] has sketched an M-Layer structure but published no detailed models. This paper presents work on an M-Layer prototype model in Section 2. Section 3 discusses some results with example applications and Section 4 concludes with a summary and indicates prospective future work.

2. M-LAYER MODELING

In human-readable documents, quantity values appear with two components: q, the numeric value, and $[Q]$, the unit symbol, as in $2.446\,\mathrm{mm}$. People rely on a textual quantity description or the context to determine the actual measurand. Since that methodology fails for machine processing, the M-Layer would extend the representation with a third element $\langle q \rangle$ that uniquely identifies the aspect in MA documents

$$q[Q] \mapsto q[Q]\langle q \rangle, \qquad (1)$$

or, e.g., $2.446\,\mathrm{mm}\ \langle\mathrm{length}\rangle$ [5], where $\langle\mathrm{length}\rangle$ represents an aspect-identifying code discussed later.

However, machines do not require multiple units per quantity, base-derived unit distinctions, or prefixes for internal processing or communication. Therefore, an M-Layer aspect would associate with one and only one unprefixed unit, in which case the aspect would uniquely determine the unit and an application may drop the unit entirely from the data. This means digital systems may simplify the data and carry $q\langle q \rangle$ in computations without ambiguity or loss of generality. In our example, the data would simply contain $2.446 \times 10^{-3}\ \langle\mathrm{length}\rangle$, assuming M-Layer documentation declares the SI9 [1] meter, e.g., as the M-Layer length unit. The data model should then allow digital systems to render this in the expected form—length, $2.446\,\mathrm{mm}$—using any unit and aspect alias the user prefers.

The form $q\langle q\rangle$ suffices for processing of digital measurement data, including all calculations, uncertainty propagation, etc. Widely interoperable MA documents, however, require more metadata to describe the measurand in order to automatically match measurement data in instrument specifications, CMCs, calibration results, calibration requests, etc. The MII (measurement-information infrastructure) taxons [9] would fulfill this requirement unless and until the M-Layer incorporates such aspect qualifiers, something not envisioned now. For example, the taxon `Measure.Length.Diameter.Outside`, where the second element `Length` links to the aspect ⟨length⟩, provides the metadata to make a digital outside-diameter value fully interoperable.

The M-Layer's core therefore comprises unambiguous aspect definitions. Table 1 illustrates a model to capture the useful data elements. The elements `AspectID` and `Name` provide the core functionality. The `ScaleTypeID`-indexed data helps define the meaningful operations on the aspect. `Definition` would aid users to distinguish one aspect from another and `Symbol` identifies the aspect's default math symbol for symbolic processing. Unlisted elements such as `Nature` (intrinsic, extrinsic, ...) and `Dimension` would add value but the M-Layer goals do not immediately require them. The M-Layer model will also allow sourcing one or more data elements from existing systems such as ontologies [11], e.g.

Table 1: `Aspects` data model.

Data Element	Description	Example
`AspectID`	unique identifier-index representing the aspect $\langle q\rangle$ in MA documents and data	⟨length⟩
`Name`	registered name	length
`Symbol`	mathematical symbol markup (e.g., LaTeX, MathML [10])	l
`Definition`	textual description or external pointer	PID to ontology entry length.definition? [11], e.g.
`ScaleTypeID`	index to the aspect's scale type	RatioScaleID

Ideally, the `AspectID` representing $\langle q\rangle$ would comprise a lightweight persistent identifier (PID). For example, the M-Layer might identify itself and its contents via a DOI (digital object identifier) [12]. As Fig. 1 shows, owners may structure their DOIs as desired. The DOI's owner-chosen suffix structure allows a hierarchical pointer that would identify, for example, the M-Layer registry; the `Aspects` dataset; and a particular aspect. For `Aspects`, the short

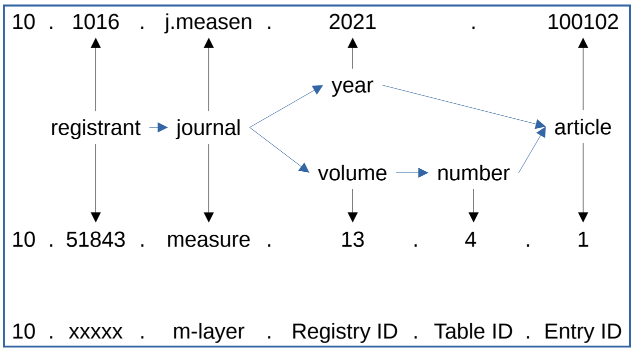

Fig. 1: A DOI-based scheme for M-Layer PIDs. The top two DOIs identify articles in two different journals, each of which has designed their own DOI structure. The bottom DOI shows one choice for M-Layer PIDs, allowing separate registries, each with a number of identified datasets containing identified entries.

`EntryID` then becomes `AspectID`, and when combined with a numerical value would both disambiguate the measurand and reduce the data size in digital documents relative to other proposals. The DOIs would easily expand to accommodate the MII taxon structure as well. The DOI's permanence as a PID ensures M-Layer availability regardless of any changes in the organization or web site hosting the registries.

A number of other datasets would supplement or complement the M-Layer; these may include datasets to register quantity-unit systems for rendering user results, scale types, base dimensions, aspect aliases (alternate quantity names) and aspect relations. If an M-Layer implementation omits any of these supplementary datasets, dependent systems and applications may augment the core M-Layer accordingly or, as previously mentioned, follow M-Layer pointers to existing systems. We omit details here due to space and the model's current fluidity—the reader may find further information at [13] as it develops—but briefly mention the most germane points.

Potential ancillary datasets: `QuantitySystems` and `UnitSystems` register systems such as Imperial, U.S. Customary, natural, CGS systems, as well as previous and future SI versions. The `Units` and `UnitAspects` datasets associate all units of interest with the correct aspect and provide *symbolic* conversion expressions to and from the aspect's M-Layer-declared unit, e.g., the SI9 equivalent. To simplify the data model and client application logic, prefixed units may have their own data entries. This would allow easy unit conversions and rendering as users desire. `ScaleTypes` and `ScaleOperations` register scales (ratio, interval, cyclic or modular, logarithmic, ordinal, nominal, empirical) and their data types and operations. For example, an interval quantity added to the associated ratio quantity yields a ratio quantity. `BaseDimensions` would define the basis for dimensional analysis. Finally, an `AspectRelations` dataset might contain mathematical expressions relating aspects, e.g., Ohm's Law. An MA-document scheme that propagated mathematical expressions for measurement models and results might start from here.

The M-Layer model also envisions an access interface such as an API, which would define a number of operations, such as retrieving the registries for local use. This would complete the M-Layer as a FAIR data source.

3. DISCUSSION

This section discusses some benefits the M-Layer should offer.

3.1. Disambiguation

Metrologists involved in digital transformation have begun to realize that quantity values as numeric value and unit do not suffice for automated consumption; nor do accompanying free-text measurand descriptions solve the problem. NCSL International's MII effort set up a test-bed database organized around quantities [14] and later initiated a measurand taxonomy project to begin addressing measurand ambiguity. The M-Layer would extend this capability beyond ratio quantities in order to handle, for example, the ordinal quantity hardness, modular angle quantities, temperature quantities on interval, ordinal, ratio, and special scales, etc.

Aspect IDs of course automatically resolve such problems as disambiguating dimensionless quantities (all using the implied unit 1) or other quantities denoted in the same unit (e.g., torque and work). So though digital documents would record for example $1.00\ \langle\text{torque}\rangle$ or $1.00\ \langle\text{work}\rangle$, both render to the same conventional form, $1.00\,\mathrm{N}\cdot\mathrm{m}$, though preferably labeled with the quantity name or MII taxon. The M-Layer would also have the option of adding base dimensions such as angle A for rotational quantities. Dimensionless quantities would work likewise, as each would have its own `Aspects` entry. For example, digital systems rendering the text "turns ratio, r: 200" or "amplifier gain A: 200" would do so from digital data containing $200\ \langle\text{turnsratio}\rangle$ and $200\ \langle\text{gain}\rangle$.

3.2. Simplified Data Processing

With the M-Layer, digital document producers may remain ignorant of the customer's preferred units and simply embed the M-Layer representations because the customer may render the values as desired or simply pass them to other digital systems. Documents that the producer converts to PDF form for the customer may do likewise.

Computations using M-Layer data may ignore measurement units and proceed as with dimensionless quantities, then simply attach the appropriate aspect ID to the final result before embedding the value in a document or otherwise communicating it. The system may ignore alternate unit systems, prefixes, and other pragmatisms because the M-Layer's units would implicitly correspond to a declared SI edition such as [1].

As a simple example, the period-to-frequency calculation

$$f = \frac{1}{T} = 1/1\,\mathrm{ms} = 1/0.001\,\mathrm{s} = 1000\,\mathrm{Hz} = 1\,\mathrm{kHz} \quad (2)$$

reduces to

$$1/0.001\ \langle\text{period}\rangle = 1000\ \langle\text{frequency}\rangle. \quad (3)$$

The latter operation both carries more information (aspect) and simplifies processing.

Many software systems therefore would require no refactoring to handle quantities properly (defining quantity-value classes, for example, and overloading their operators to deal with dimensions). Also, having an `AspectRelations` dataset available in the M-Layer would help standardize metrological computations; for example providing commonly used expressions such as moist-air density.

3.3. Unit Conversions

The usual unit conversions of course remain trivial with an M-Layer. User interfaces would translate conventional notations to and from M-Layer representations but all intermediate processing and communications between M-Layer-aware systems would entail no conversions.

This M-Layer model includes *symbolic* conversion *functions* to eliminate precision-limited conversion constants. Thus, digital systems using sufficiently precise, arbitrary-precision, or symbolic computations for all operations would introduce no further errors or uncertainty into results, at least up to a user interface. So a system may postpone numeric conversions until required by encoding them symbolically as, e.g., LaTeX or MathML. An angle value, for example might digitalize as (4)'s right hand side,

$$44.236^\circ = 44.236\pi/180\ \langle\text{planeangle}\rangle, \quad (4)$$

where the symbolic conversion expression $x\pi/180$ comes from the M-Layer `Units` dataset entry for degree and assumes the SI radian as the M-Layer angle unit. Similarly, conversion *functions* allow arbitrary scale conversions such as

$$L_{x/x_0} = \log\left(\frac{x}{x_0}\right), \quad (5)$$

which converts from a dimensionless ratio-scale quantity to a logarithmic-scale level quantity.

3.4. Scale Handling

The ML would handle scale conversions similarly to unit conversions. Since every `AspectID` associates with a unique `ScaleTypeID`, we may add the aspect

$\langle$1990ConventionalVoltage$\rangle$ tied to an empirical scale based on the conventional Josephson constant K_{J-90} with a scale conversion entry such as $\frac{K_{J-90}x}{K_J}$, where $K_J = \frac{2e}{h}$ with constants e and h defined to match the declared M-Layer references, e.g. SI9 [1]. This would allow automated systems to easily correct past (digital) measurement data according to new definitions. The ML would likewise define other empirical scales, such as the ITS-90 temperature scale and mercury-based temperature scales [3] for various atmospheric pressures in order to capture the differences from their associated SI-defined aspects.

Defining ordinal scales pulls such quantities as hardness into the same digital system without requiring ad hoc modifications. Modular scales would handle angular quantities when restricting values to a certain range, such as $0°$ to $360°$. From these examples, the reader will see the avenues an M-Layer opens to digital transformation.

4. CONCLUSION

This paper has presented initial steps toward modeling and prototyping an M-Layer to support FAIR digital measurement data and systems. For human-readable documents, the M-Layer changes nothing, except perhaps to facilitate their generation. By replacing unit symbols and textual measurand descriptions with unique aspect IDs, the M-Layer concept offers machine-readability, global interoperability, and generalized quantities (aspects) and units (scales) to handle all types of measurements in digital documents and measurement software systems.

In collaboration with international partners, the NCSL International 141 MII and Automation Committee plans to continue developing the M-Layer model and populating a prototype with intention to replace the MII test-bed quantities and units database for use in digital documents. In cooperation with industry partners, we have begun drafting use cases, a product definition, and requirements from the user viewpoint. As the MII committee continues its collaboration with the international quality infrastructure, the M-Layer should become a FAIR-data resource. The conference presentation will demonstrate software that uses a prototype M-Layer.

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