

Towards a unification of measurement, AI, quality and sustainability: foundations and principles

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Abstract. Measurement, artificial intelligence (AI), quality, and sustainability are traditionally treated as distinct domains. To underpin and advance the science and technological developments, it is important and beneficial to develop a principled unifying framework for these fields. This paper first examines the deep connections of the concepts, models and mathematical characterisations of measurement, AI, quality and sustainability, and then proposes three foundational principles, formulated as three Laws to guide the integration of these domains, including Law of Oneness, Law of Dual Processes and Law of Measurement and Control Duality. These principles further lead to a generalised communication model supporting the unification of the four domains. They together will facilitate the advancement of the fields of measurement, AI, quality and sustainability, and underpin the development of the core science and technologies of Industry 4.0 and future Industry 4.0+.

1 Introduction

Last decade has witnessed a new phase in human history, marked by unprecedented challenges and rapid technological advancements on a global scale. Humanity faces multiple crises and challenges including persistent conflicts, global health crises, economic inequality, climate change and rapid technological disruptions. The latter stems from a powerful technology stack that is maturing and accelerating under Industry 4.0, including IoT, robots, VR/AR, edge/cloud computing, and especially the explosive growth of artificial intelligence. These forces are driving deep convergence across engineering, measurement, intelligent systems, quality and sustainability: AI models are being embedded into measurement and quality engineering; sustainability metrics are increasingly based on sensor-based monitoring; and measurement adds active links in cyber-physical systems. The challenges and trends demand for a system thinking and a big integration of a principled framework that can connect and indeed unify measurement, AI, quality, and sustainability. This paper will propose such a framework based on the examinations of the related concepts, models and mathematical formulations, and formulate the key principles as three laws. These principles further lead to a generalised communication model supporting the unification of measurement, AI, quality and sustainability.

2 Conceptual connections

We begin with definitions of measurement, AI, quality and sustainability.

2.1 Measurement

Measurement may be defined as the assignment of numbers or other symbols, by an objective, empirical process, to attributes of objects or events of the real world, in such a way as to describe them (according to defined rules) [1].

Metrology (i.e. measurement science) consists of various measurement standards, instruments and measurement theory. The latter itself covers representation, measurement error and measurement uncertainty.

2.2 AI

According to the Oxford English Dictionary, artificial intelligence is the capacity of computers or other machines to exhibit or simulate intelligent behaviour. “Intelligent” means able to understand – to grasp meaning, purpose, and underlying truth, so AI concerns systems that can comprehend and act on underlying truth, which is clearly connected with measurement.

Machine learning is the core of AI. According to Mitchell [2], “a computer program is said to learn from experience E with respect to some class of tasks T and performance measure P, if its performance at tasks in T, as measured by P, improves with experience E”. In general AI systems are agents that improve representations and decisions through experience [3].

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2.3 Quality

Quality is the degree to which inherent characteristics fulfil requirements [4]. This entails both measurement and control, also AI which helps improve system performance and decision making based on experiences.

2.4 Sustainability

Sustainability has been defined as “meeting our own needs without compromising the ability of future generations to meet their own needs [5].” It has three dimensions or pillars: environmental, economic, and social, although many definitions emphasize the environmental dimension.

It should be obvious that sustainability may be viewed as the generalized quality since the quality and sustainability means meeting the needs or requirements of the customers, stakeholders and the societies. Indeed, TQM’s definition as “management approach of an organization, centred on quality, based on the participation of all its members and aiming at long-term success through customer satisfaction, and benefits to all members of the organization and to society” [4] has already shown the close connections between quality and sustainability. Since sustainability can be viewed the generalised quality, in the rest discussions in this paper, we shall mainly focus on the relationships among measurement, AI and quality.

3 Model connections

The connections between measurement, AI, quality and sustainability can also be seen from their models.

The functional model of a measurement system is shown in Fig. 1. It is worth noting it is closely related to the knowledge pyramid shown in Fig. 2. The knowledge pyramid [6] has the real world (objects and phenomena) at the base and knowledge at the apex. In between are the successive layers representing the three levels of abstraction: human perception → properties/attributes + propositions → machine perception → symbolic data → data manipulation → knowledge, highlighting the shift from sensing to data to symbol based knowledge and reasoning. Machine learning may be utilised in Signal Processing and Data Manipulation, but the AI scope covers the full measuring chain and the whole knowledge pyramid due to its focus on the underlying truth.



Fig. 1 Functional model of a measurement system [7]

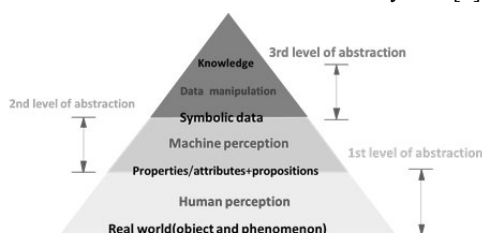


Fig. 2 Knowledge pyramid [6]

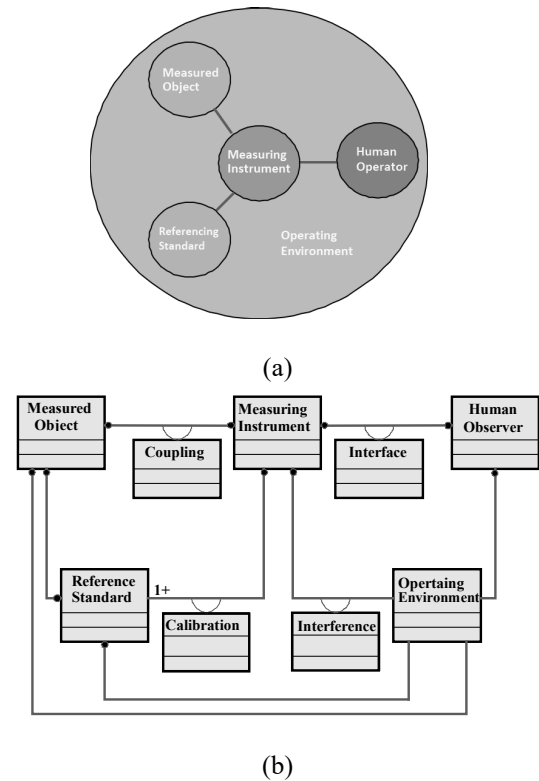


Fig. 3 Object-oriented model of a measurement system [7]

An object-oriented model (OOM) of measurement system is shown in Fig. 3 [7]. It captures the internal, operational and environmental aspects of a measurement system. The OOM can well model the five objects (Fig. 3a) of a measurement system: measured object, measuring instrument, reference standard and human operator and operating environment, and their interactions, including coupling, calibration, interface and interferences (Fig. 3b).

Interestingly, the OOM can be readily modified to represent AI, as shown in Fig. 4, which is closely related to Mitchell’s definition of machine learning “from experience E with respect to some class of tasks T and performance measure P, if its performance at tasks in T, as measured by P, improves with experience E”. The task T is the specific interaction engaging the learning agent to interact with the task object through the sensor(s) and actuator(s) in the operating environment. The outputs of the sensor(s) and the inputs to the actuators are the experience E of the agent. The performance P is the direct comparison between the actual and ideal states in the object.

Similarly, the OOM can be applied to quality engineering. In fact, the OOM of AI can be directly interpreted for quality engineering (QE) or quality management (QM). The quality management model given in the ISO 9000 is essentially a PDCA cycle (Fig. 5) and the OOM for the PDCA cycles is shown in Fig. 6. The flows from the quality agent to actuators to the task object are essentially the P and D, while the opposite flows from the task object to sensors to the agent are the C and A. Therefore, the PDCA is embedded in the OOM.

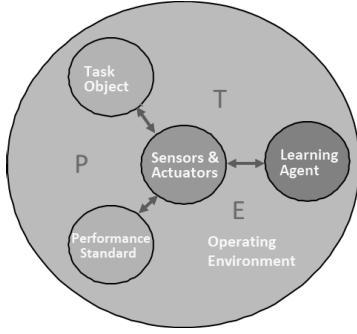


Fig. 4 OOM for AI

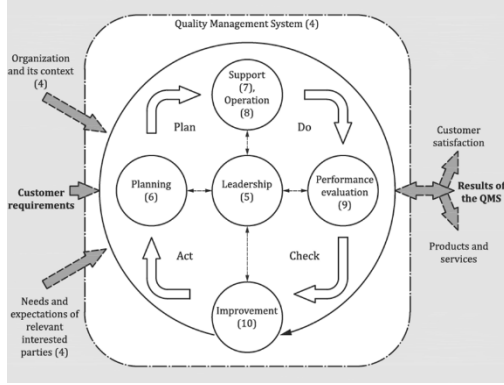


Fig. 5 PDCA cycle of quality management [4]

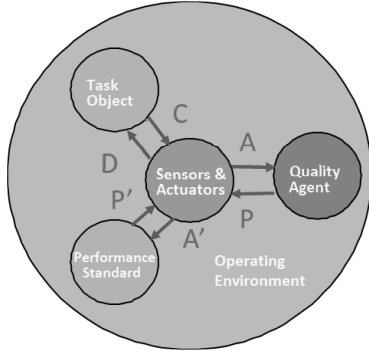


Fig. 6 OOM for PDCA cycle of quality management

One logical and interesting conclusion of these models is that AI is an instrument and QE/QM is also an instrument.

4 Fundamental processes of the measurement, AI and quality

In the above OOMs for measurement, AI and quality, there are two fundamental processes: measurement and control:

- **Measurement process:**

$$T.A \xrightarrow{c} O.B \xrightarrow{a} O.C \quad (1a)$$

Or in short form:

$$(T.A, O.C] \quad (1b)$$

where $T.A$ is the attribute or measurand of the entity T ; $O.B$ is the sensor output as the binding attribute between the entity and the observer; $O.C$ is the observer or agent's concept or representation. c is the sensing

function, a is the processing function. The square bracket “[“ or “]” indicate the ownership of the attribute by the agent or observer O .

- **Control process:**

$$O.C \xrightarrow{p} O.B \xrightarrow{d} T.A = [O.C, T.A] \quad (2)$$

where $O.C$ is the agent's intention; $T.A$ is the attribute of the object to be controlled; $O.B$ is the binding attribute between the controller and the object; p is the planning function; d is the execution of the plan.

Additionally there is an implicit communication process:

- **Communication process:**

$$O_1.C_1 \xrightarrow{p} O_1.B_1 \xrightarrow{d} T_1.A_1 \xrightarrow{\text{channel}} T_2.A_2 \xrightarrow{c} O_2.B_2 \xrightarrow{a} O_2.C_2 \quad (2a)$$

or in shorter forms as:

$$[O_1.C_1, T_1.A_1] \rightarrow [T_2.A_2, O_2.C_2] = [O_1.C_1, O_2.C_2] \quad (3b)$$

Based on the basic processes of measurement, control and communication, we can also model the indirect measurement, indirect control and other more complicated processes.

For an indirect measurement, we have:

$$(T.A, O_1.C_1][O_1.C_1, O_2.C_2] = (T.A, O_2.C_2] \quad (3)$$

The indirect control is just the dual of indirect measurement. Further it is also possible to model more general information and knowledge processes, e.g. Markov decision process pipelines. These structures can be developed further to model various processes in measurement, AI, quality and sustainability, e.g. active measurement, closed-loop control, various machine learning and AI problems, and quality engineering tools. Essentially these processes or structures are functions mapping the underlying truth or ideal states to their best representation or realisation by the agent.

Another deep connection of these fields is uncertainty. Measurement uncertainty is the core of measurement theory. The uncertainty in a quality system is in fact quality (i.e. uncertainty is essentially a measure of the quality). AI can generally acquire, represent and utilise information and knowledge, which are quantified by entropy that is really uncertainty.

5 Unifying principles

Based on the concepts, models and fundamental processes of measurement, AI and quality, we can formulate the unifying principles of these fields as the following laws.

5.1 Law of Oneness

The first law, Law of Oneness, can be formulated as follows:

Given the measurable attributes of an entity in its environment, an agent's representation of these attributes is asymptotically convergent toward their true states.

$$\lim_{t \rightarrow \infty} O.C(t) = T.A \quad (5)$$

where T.A is the true state of the entity T; O.C(t) is the agent O's concept or representation at time t.

5.2 Law of Dual Processes

The second law, the Dual Process Law, can be stated as follows:

Every agent–entity interaction necessarily involves a binding attribute and two subprocesses which are asymptotically inverse to each other.

For the perception/measurement view, we have:

If

$$T.A \xrightarrow{s} O.B \xrightarrow{p} O.C \quad (6a)$$

then

$$\lim_{t \rightarrow \infty} p(t) \circ s(t) = I \quad (6b)$$

where s is the sensing function, p is the processing function.

5.3 Law of the Measurement–Control Duality

The third law, the Measurement–Control Duality Law, is as follows:

Under appropriate regularity, measurement (estimation) and control are dual processes, differing primarily in the direction of information flow.

$$\mathcal{M}: T.A \rightarrow O.C \xleftrightarrow{\text{dual}} C: O.C \rightarrow T.A \quad (7a)$$

or

$$(T.A, O.C] \xleftrightarrow{\text{dual}} [O.C \rightarrow T.A) \quad (7b)$$

Applying the third law to the first two laws, we can derive the control versions of the first two laws.

6 Unification under the Laws of Oneness and Dual Processes via the generalised communication model

According to the Laws of Oneness and Dual Processes, all four domains can be viewed as special cases of the generalised communication model.

- **Measurement:** The measurand T.A is the measured quantity with a conventional true value, which can be regarded as the perception result of an ideal observer. It is encoded by the sensor and decoded by the processing and calibration. The measurement result O.C will approach the conventional true value by an ideal observer according to the Law of Oneness.

- **AI:** A typical supervised learning may be modelled as a generalised measurement process, the T.A

corresponds to ground truth, while O.C represents the model's prediction based on the O.B (input to the model). By adjusting the processing components of the model, such as the gradients of weights in neural networks, the loss (the difference between the predictions and the ground truth) is minimised. The system thus learns to align predictions with truth, consistent with backpropagation.

- **Quality Management:** QM can be viewed as a communication process (PD, CA), where PD=[O_c.C₁, O_m.B₁, T.A], CA=(T.A, O_m.B₂, O_m.C₂], P=[O_c.C₁, O_m.B₁], D=[O_m.B₁, T.A], C=(T.A, O_m.B₂], A=[O_m.B₂, O_m.C₂], O_c is customer and O_m manufacturer. The customers' requirements O_c.C are translated to the manufacturing plan O_m.B₁, producing the product T.A, which is measured with results O_m.B₂ and the action O_m.C₂.

- **Sustainability:** Sustainability can be treated as generalised quality, encompassing economic, social, and environmental dimensions. In the PDCA cycle, the requirements come from societal needs (e.g. Net Zero goals), and the plans are sustainability strategies and policies, and the states are checked with monitoring and lifecycle assessment, followed by the further actions and improvements.

7 Worked example: error analysis for a general measurement chain

Given a general measurement system with a unknown measured vector x_1^* passing m transducing elements, $T_1, \dots, T_m$ (x_i^* before element T_i , ($i = 1, 2, \dots, m$)), and the output y^* is measured as y . The interpretation chain has m processing elements $P_m, \dots, P_1$, matching the m transducing elements.

$$x_1^* \xrightarrow{T_1, \dots, T_m} y^* \xrightarrow{T_{meas}} y \xrightarrow{P_m, \dots, P_1} x_1 \quad (8)$$

Ideally $P_k = T_k^{-1}$. In general, each interpretation space mismatch is $\Delta P_k = P_k - T_k^{-1}$.

Linearize each pair around its local truth x_{k+1}^* :

$$\Delta P_k(x) = \Delta A_k x + \Delta t_k \quad (9)$$

Let $\phi_{1:k-1} = P_1 P_2 \dots P_{k-1}$ to be the prefix composite interpretation (PCI). In the first-order expressions we evaluate at the nominal model and have the nominal PCI: $\phi_{1:k-1}^{(0)} = P_1^{(0)} P_2^{(0)} \dots P_{k-1}^{(0)}$, then the measurement error of x_1^* is given by:

$$e = \hat{x}_1 - x_1^* \approx \sum_{k=1}^m \phi_{1:k-1}^{(0)} (\Delta A_k x_{k+1}^* + \Delta t_k) + \phi_{1:m}^{(0)} \Delta y \quad (10)$$

This approach to error analysis can be applied to all measurement processes and systems (such as coordinate measuring machines), including generalised measurement processes.

8 Conclusion

The deep connections of the concepts, models and mathematical characterisations of measurement, AI, quality and sustainability have been discussed. The unification of measurement, AI, quality and sustainability is possible with a coherent framework. The principles formulated as three fundamental laws underpin a unified treatment of measurement, intelligence and system improvement. This will open up a range of new research directions, e.g. AI as instrument, Quality AI (QAI) and Industry 4.0+ (which may be defined as Industry 4.0 plus sustainability and the unified approach to measurement, AI, quality and sustainability). They will help advance the fields of measurement, AI, quality and sustainability and underpin the development of the core science and technologies of Industry 4.0 and future Industry 4.0+.

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