Physical Units Representation in IEEE 1451.2

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The IEEE 1451.2 Standard working group has developed a simple and easily stored method for identifying physical units when working with smart transducers, allowing them to provide output in terms any user can understand. This becomes even more necessary if the transducer must plug into any system and be useable without writing special software. The approach chosen by the IEEE 1451.2 working group is not without compromises but it fits in almost any application. Providing a calibration Transducer Electronic Data Sheet (TEDS) to allow the system to automatically load the calibration constants for the transducer is one of the decisions that allowed them to reach this goal. However, just allowing the manufacturer to specify the calibration constants in the device does not allow the transducer to work in any system without writing special software. For example, what units should be used when calibrating a pressure transducer? It could be pascals or kilopascals or maybe megapascals. If you don't want some form of pascals then how about using pounds per square inch (psi) or inches of mercury? Maybe a user would want inches of water or even inches of alcohol. All of these units are regularly for pressure. There is no end to the possible units that different users want. To allow a manufacturer to build a transducer with built in calibration constants, the physical units must be specified.

There are two basic approaches to specifying the units that the working group could have used. One choice would have been to try to provide a table of all possible units and to use an enumeration to select which one is being used in the transducer. The difficulty with this choice is that the total number of possible units is almost limitless. The table would be huge and still would not include all possible units. The other choice is to define a small set of basic units that can be combined to provide the required units. The standard then needs to find a way of specifying how to combine these basic units to provide the units for the particular transducer. Not all units that a user might desire can be provided in this fashion but a set that is adequate for most transducers can be defined. The conversion between the units specified in the standard and what the user wants to see is usually a simple multiplication operation the system needing to display the data can handle.

By providing a set of units for the manufacturer or calibration lab to use when determining the calibration constants, the calibration can always be performed the same way. The process of displaying the data in whatever units the user expects is then left up to the user's system. This division of responsibility allows each organization to do its job independent of the other and still produce the desired results. More robust systems will result if these procedures are followed.

The working group needed to specify a consistent set of units and to find a practical way to incorporate them into the transducer. Other standards bodies have addressed the problem of finding a consistent set of units. The IEEE 1451.2 working group selected an appropriate set and refered to it in the standard. The standard selected is the International System of Units established in 1960 by the 11th General Conference on Weights and Measures. The abbreviation SI from the French Le System International d'Units is normally used to identify this set of units. It is based upon the metric system of measurement used around the world.

Table 1 gives the seven base quantities, assumed to be mutually independent, on which the SI is founded; and the names and symbols of their respective units, called "SI base units." Definitions of the SI base units are given in *The International System of Units (SI)*, edited by B. N. Taylor, National Institute of Standards and Technology, Special Publication 330, 1991 Edition (U.S. Government Printing Office, Washington, DC, August 1991).

Table 1 SI base units

Base quantity	Name	Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

SI Derived Units

Derived units are expressed algebraically in terms of base units. In the column labeled "Expression in terms of other SI units" of Table 2 some of the units are in terms of other derived units. However, before they can be represented in accordance with the standard they must be converted into the base units as shown in the column labeled "Expression in terms of SI Base units." The symbols for derived units are obtained by means of the mathematical operations of multiplication and division. For example, the derived unit for molar mass (mass divided by amount of substance) is the kilogram per mole that has the symbol kg/mol. Table 2 contains examples of derived units expressed in terms of SI base units.

Table 2 Units derived from the SI Base Units

Derived quantity	Special name	Special symbol	Expression in terms of other SI units	Expression in terms of SI Base units
plane angle	radian	rad		$m\ m^{-1}=1$
solid angle	steradian	sr		$m^2\ m^{-2}=1$
frequency	hertz	Hz		s^{-1}
area (square meter)				m^2
volume (cubic meter)				m^3
acceleration (meter per second				m/s^2

squared)				
wave number (reciprocal meter)				m^{-1}
mass density(density) (kilogram per cubic meter)				kg/m^3
specific volume (cubic meter per kilogram)				m^3/kg
current density (ampere per square meter)				A/m^2
magnetic field strength (ampere per meter)				A/m
amount-of-substance concentration (mole per cubic meter)				Mol/m^3
luminance (candela per square meter)				cd/m^2
force	newton	N		$m\ kg\ s^{-2}$
pressure, stress	pascal	Pa	N/m^2	$m^{-1}kg\ s^{-2}$
energy, work, quantity of heat	joule	J	N m	$M^2\ kg\ s^{-2}$
power, radiant flux	watt	W	J/s	$m^2\ kg\ s^{-3}$
electric charge, quantity of electricity	coulomb	C		s A
electric potential, potential difference, electromotive force	volt	V	W/A	$m^2kg\ s^{-3}A^{-1}$
capacitance	farad	F	C/V	$m^{-2}\ kg^{-1}\ S^4\ A^2$
electric resistance	ohm	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
electric conductance	siemens	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
magnetic flux	weber	Wb	V s	$m^2\ kg\ s^{-2}\ A^{-1}$
magnetic flux density	tesla	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
inductance	henry	H	Wb/A	$m^2\ kg\ s^{-2}A^{-2}$
Celsius temperature	degree Celsius	°C		K
luminous flux	lumen	lm		cd sr
illuminance	lux	lx	lm/m^2	m^{-2} cd sr

The working group decided to include the SI base units plus the derived units radian and steradian as base units for the standard. This gave a set of nine units from which the physical units required for the transducer are derived by the mathematical operations of multiplication and division. What remained was to devise a way to include the information in the transducer.

From an examination of Table 2 it becomes apparent that any particular unit can be represented as the product of a set of the base units with each unit raised to the appropriate power. Since zero is a legitimate power, it can be seen that a particular unit can be represented by the product of all of the base units with each of the base units raised to the appropriate power. For example, for a sensor that measured distance and a user could write the units for this device in terms of the seven SI base units by writing the following:

$m^1\ kg^0\ s^0\ A^0\ K^0\ mol^0\ cd^0$.

However, units are seldom written with an exponent of “0” and if the exponent is “1” it is understood and not written. The units for the distance measuring device are written simply as “m.” Computers need more explicit instructions such as a table that contains all of the exponents in a certain order. The example above could be written 1,0,0,0,0,0,0 and mean $m^1\ kg^0\ s^0\ A^0\ K^0\ mol^0\ cd^0$.

This is the basis of the method of representing physical units that the standard uses. The working group decided to add the two derived units radians and steradians to the seven SI base units. This gives only nine basic units for the standard. There are however some devices that measure the ratio of two quantities with the same units. For example strain is in terms of meters per meter that is expressed as m/m, m^1m^{-1} or m^0. This results in what is called a “dimensionless” quantity. It is still desirable to know that the device is measuring something in terms of a physical unit. This situation requires special handling in any system of units. There are also quantities that are measured in terms of the logarithm of a quantity or in terms of the logarithm of a “dimensionless” ratio. All of these require some method of identifying them so that we can interpret them. Two categories of units that are not expressed in terms of the base units are the arbitrary units such as hardness and “digital data." The system must be able to identify these quantities. This can be accomplished by an identifier that defines classes of units.

The exponents can in theory be anything and should logically be represented as floating point numbers but as a practical matter exponents almost always lie between ±four and a resolution of 1/2 is adequate. Two related matters with nothing to do with units now come into play. The first is that the smallest unit in the standard is the eight bit byte or octet. The other is that there was no way defined in the standard to express a signed integer. Since no other area of the standard requires signed integers, the exponents are encoded using an unsigned byte integer. To give a resolution of 1/2 the exponent is multiplied by two. To represent the exponent as a signed quantity, 128 is added to the exponent after it is multiplied by two. This means that exponents between -64 and +63 can be expressed.

The following paragraph and table, which are taken from the standard, give the method of encoding the data type “physical units.”

Physical units

Symbol: UNITS
Size: 10 bytes
A binary sequence of ten bytes that encode physical units as described in Table 3. Each of the fields shall be interpreted as an unsigned integer. A unit shall be represented as a product of the SI base units, plus radians and steradians, each raised to a rational power. This structure encodes only the exponents; the product is implicit.

Table 3 Physical units data type structure

Field #	Description	# bytes
1	ENUMERATION 0: Unit is described by the product of SI base units, plus radians and steradians, raised to the powers recorded in fields 2 through 10.	1
	1: Unit is U/U, where U is described by the product of SI base units, plus radians and steradians, raised to the powers recorded in fields 2 through 10.	
	2: Unit is $\log_{10}(U)$, where U is described by the product of SI base units, plus radians and steradians, raised to the powers recorded in fields 2 through 10.	
	3: Unit is $\log_{10}(U/U)$, where U is described by the product of SI base units, plus radians and steradians, raised to the powers recorded in fields 2 through 10.	
	4: The associated quantity is digital data (e.g. a bit vector) and has no unit. Fields 2-10 shall be set to 128. The "digital data" type applies to data that represents counting, such as the output of an ADC, or that represents a state, such as the current positions of a bank of switches.	
	5: The associated physical quantity is represented by values on an arbitrary scale (e.g. hardness). Fields 2-10 are reserved, and shall be set to 128.	
	6-255: Reserved	
2	(2 * <exponent of radians>) + 128	1
3	(2 * <exponent of steradians>) + 128	1
4	(2 * <exponent of meters>) + 128	1
5	(2 * <exponent of kilograms>) + 128	1
6	(2 * <exponent of seconds>) + 128	1
7	(2 * <exponent of amperes>) + 128	1
8	(2 * <exponent of kelvins>) + 128	1
9	(2 * <exponent of moles>) + 128	1
10	(2 * <exponent of candelas>) + 128	1

The U/U forms (enumeration’s one and three) are for expressing “dimensionless” units such as strain (meters per meter) and concentration (moles per mole). The numerator and denominator units are identical, each being specified by subfields two through ten.

Boolean data (values in {0, 1} or {False, True}) shall be represented as digital data (enumeration 4) with Channel Data Model Length = 1 and Channel Model Significant Bits = 1. See 5.2.3.14 through 5.2.3.16 of the standard for further definition of these quantities.

Examples

Table 4 gives the fields for the units for distance that are expressed in meters. The use of enumeration 0 signifies that the units are the product of the base units. Since the meter is a base unit only the exponent for meters is non-zero.

Table 4 Distance (m)

	Enum	rad	sr	m	kg	s	A	K	mol	cd
exponent	0	0	0	1	0	0	0	0	0	0
decimal		128	128	130	128	128	128	128	128	128

Table 5 shows the table for the units when the quantity represents an area. The enumeration is zero to indicate that the units are derived by multiplying the exponents for the base units. Since only the base unit for distance is involved the only non-zero exponent is for the meter. Since the units for area are m*m the exponent is two.

Table 5 Area (m^2)

	Enum	rad	sr	m	kg	s	A	K	mol	cd
exponent	0	0	0	2	0	0	0	0	0	0
decimal		128	128	132	128	128	128	128	128	128

Table 6 shows the table for the measurement of pressure. The derived units for pressure are pascals. This involves three of the base units, the meter, the kilogram and the second.

Table 6 pressure (pascals = m^{-1} kg s^{-2})

	Enum	rad	sr	m	kg	s	A	K	mol	cd
exponent	0	0	0	-1	1	-2	0	0	0	0
decimal		128	128	126	130	124	128	128	128	128

The table for the representation of electrical resistance is given in Table 7. As shown in the table this unit requires four of the base units.

Table 7 Resistance (ohms = m^2 kg s^{-3} A^{-2})

	Enum	rad	sr	m	kg	s	A	K	mol	cd
exponent	0	0	0	2	1	-3	-2	0	0	0
decimal		128	128	132	130	122	124	128	128	128

As shown in Table 8 Noise Spectral Density also involves four of the base units. The interesting thing about this unit is the use of the square root function that causes the exponent for seconds to be -5/2.

Table 8 Noise Spectral Density - volts per root Hertz (V/√hz = m^2 kg $s^{-5/2}$ A^{-1})

	Enum	rad	sr	m	kg	s	A	K	mol	cd
exponent	0	0	0	2	1	-5/2	-1	0	0	0
decimal		128	128	132	130	123	126	128	128	128

Table 9 describes the units for mass fraction. Mass Fraction is a “dimensionless” quantity that is represented by mol/mol. Thus the enumeration 1 is used to specify a ratio of the same units.

Table 9 Mass Fraction (mol/mol)

	Enum	rad	sr	m	kg	s	A	K	mol	cd
exponent	1	0	0	0	0	0	0	0	1	0
decimal		128	128	128	128	128	128	128	130	128

Table 10 describes the units for strain. Strain is a "dimensionless" quantity represented by m/m. Thus the enumeration 1 is used to specify a ratio of the same units. The remaining fields are the same as for the distance measurement in Table 4.

Table 10 strain (m/m)

	Enum	rad	sr	m	kg	s	A	K	mol	cd
exponent	1	0	0	1	0	0	0	0	0	0
decimal		128	128	130	128	128	128	128	128	128

The measurement of radiated power is normally accomplished in decibels. As shown in Table 11 the representation of this quantity using the base units uses the unit of bels that is ten decibels.

Table 11 Power Quantity - Bel (log10 W/W) W = m^2 kg s^{-3}

	Enum	rad	sr	m	kg	s	A	K	mol	cd
exponent	3	0	0	2	1	-3	0	0	0	0
decimal		128	128	132	130	122	128	128	128	128

Suppose that a transducer is counting widgets as they pass a station on a conveyor belt. The appropriate unit for this transducer is "widgets." It is not possible to derive the unit "widgets" from the nine base units defined in the standard. For this case there are two possibilities provided in the standard. The standard allows either enumeration 0 or enumeration 4 to be used to identify the units. The exponents would all be set to 0. Since the output of the transducer represents a quantity, enumeration 0 is the preferred enumeration. The working group should consider revising the standard to remove this alternative at a future date. Table 12 is an example of this type of units. Note that for this case some special software will be required to display the appropriate units.

Table 12 Counts

	Enum	rad	sr	m	kg	s	A	K	mol	cd
exponent	0	0	0	0	0	0	0	0	0	0
decimal		128	128	128	128	128	128	128	128	128

The output of the transducer could represent the settings of a bank of switches or a command to open or close a valve. The units may be things like "on," "off," "up," "closed" or almost anything else. These units cannot be expressed in terms of the nine base units defined in the standard. Since it does not represent a quantity, enumeration 4 is the proper choice. Table 13 is an example of the units for this type of transducer. Special software will be needed in the user's system to handle this type of transducer.

Table 13 Switch Positions

	Enum	rad	sr	m	kg	s	A	K	mol	cd

exponent	4	0	0	0	0	0	0	0	0	0
decimal		128	128	128	128	128	128	128	128	128

System Considerations

These tables can represent almost any physical unit using only ten bytes of memory. The standard does not address how to convert between the system of units selected for the standard and the units that the user expects to see displayed. It leaves it up to the user's system to determine how to display the data. In general the user's system will include tables of conversions to convert between the base units and the units that the operator wants displayed. These can and will be different for every system and still not affect the way that the calibration is performed. A related issue is that the data is probably not scaled the way that the operator is used to seeing. For example pressure is often displayed in kilopascals or megapasals if not in pounds per square inch or inches of mercury. Scaling of the data is also left as a function in the user's system. In almost all cases these conversions involve multiplying by a constant to convert between different units. The noteworthy exception to this is for temperature where it is necessary to subtract one constant and multiply by another. Just where in the user's system the conversions should be performed is a system design issue that the standard does not address. If all users of the data expect to see the data in the same units the conversion could be performed with an application written to run in the network interface that the standard refers to as a Network Capable Application Processor or NCAP. If different operators want to see different units then the conversions probably should be performed at the display station or in a host processor that drives the display.

Conclusions

The IEEE 1451.2 Standard has provided the beginning of a consistent set of tools to address the issue of displaying data in a standardized way. By providing a way for a set of base units to be incorporated into the transducer the working group has standardized the way that the units are represented in the TEDS and the way that the calibration coefficients are represented. This means that a transducer that is build and calibrated per the standard should be able to plug into any system. That system should then be able to display most data without any other changes to the system.

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