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General requirements for cyber-physically controlled smart machine tool systems (CPSMT) — Part 3: Reference architecture of CPSMT for additive manufacturing

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Foreword

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This document was prepared by Technical Committee ISO/TC 184, *Automation systems and integration*, Subcommittee SC 1, *Industrial cyber and physical device control*.

A list of all parts in the ISO 23704 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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Introduction

According to ISO/ASTM 52900, additive manufacturing (AM) is the process of joining materials to make a part from 3D model data usually layer by layer. With the advancement of various feedstocks, process technologies, and product design methodologies, AM contributes to realizing customized production, which is the key objective of Industry 4.0. Also, AM allows construction of complex geometry and other features that were previously impossible or impractical to manufacture.

Many institutions have long been devoted to technological development from the viewpoint of reducing downtime and defects and are considering smart technologies such as Internet-of-Things (IoT) as a new means to achieve this.

From the market perspective, many institutions have released various smart additive manufacturing systems (SAMS) based on their own concepts and local terminologies. This makes stakeholders confused about the common concept of SAMS, including end-users. For this reason, standards and substantial modeling for a SAMS are needed.

From the standards perspective, for standards on contemporary AM technology, there is a set of standards and a roadmap from ISO TC261/ASTM F42. For standards on smart manufacturing, RAMI 4.0 (IEC/PAS 63088) and IEC TR 63319 TR-SMRM provide a reference model for smart manufacturing on a high level. Even though some standards deal with Industry 4.0 enabling technologies, e.g. OPC-UA (IEC/TR 62541-1 and [67]), MTConnect (ANSI/MTC1.4-2018), ISO/IEC 30141, IEC 62769, there are no standards specifying the SAMS.

The ISO 23704 series specifies general requirements on smart machine tools for supporting smart manufacturing in the shop floor via cyber-physical system control scheme, namely cyber-physically controlled smart machine tool systems (CPSMT).

Figure 1 shows the overall structure of the ISO 23704 series, including:

— Overview and fundamental principles of CPSMT in ISO 23704-1;

— Reference architecture of CPSMT for subtractive manufacturing in ISO 23704-2;

— Reference architecture of CPSMT for AM in ISO 23704-3.

Other related parts such as implementation guideline or reference architecture for other types of manufacturing will be added if and when necessary

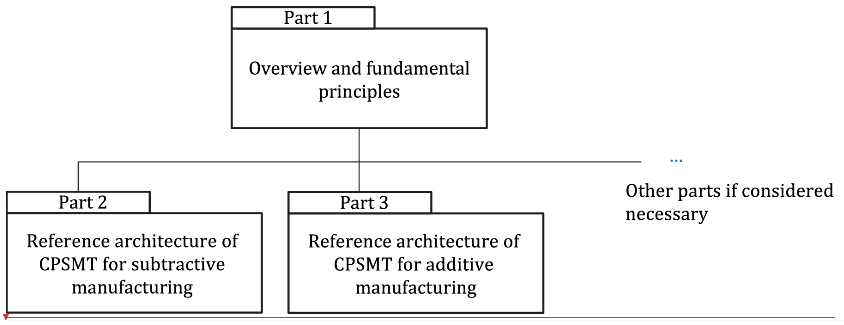

Figure 1 — Overall structure of the ISO 23704 series on general requirements for cyber-physically controlled smart machine tool systems (CPSMT)

This document can be used as a reference and guidelines for stakeholders such as, but not limited to:

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— Design engineers in the area of SAMS,

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— System architects in the area of SAMS,

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— Software engineersworking with the AM machine builders in the area of SAMS,

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— Machine tool control vendors in the area of SAMS,

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— Solution and service providers in the area of SAMS, and

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— End users such as factory operators working with SAMS.

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General requirements for cyber-physically controlled smart machine tool systems (CPSMT) — Part 3: Reference architecture of CPSMT for additive manufacturing

1 Scope

This document specifies a reference architecture of cyber-physically controlled smart machine tool systems (CPSMT) for additive manufacturing (AM) based on the reference architecture of CPSMT as provided in ISO 23704-1 and the requirements for cyber-physically controlled smart additive manufacturing system.

The reference architecture of a CPSMT for AM includes:

— the technical requirements for the smart additive manufacturing system (SAMS),

— the reference architecture of the cyber-physically controlled machine tools (CPCM) for AM,

— the reference architecture of the cyber-supporting system for machine tools (CSSM) for AM, and

— the interface view of the CPSMT for AM.

This document also provides:

— stakeholder requirements for the SAMS,

— the concept of the digital thread,

— types of abnormality in AM, and

— use cases of reference architecture of a CPSMT for AM.

This document does not specify physical or implementation architecture.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements for this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 23704-1, *General requirements for cyber-physically controlled smart machine tool systems (CPSMT) — Part 1: Overview and fundamental principles*

ISO 23704-2, *General requirements for cyber-physically controlled smart machine tool systems (CPSMT) — Part 2: Reference architecture of CPSMT for subtractive manufacturing*

ISO/ASTM 52900, *Additive manufacturing — General principles — Fundamentals and vocabulary*

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3 Terms, definitions and abbreviated terms

For the purposes of this document, the terms and definitions given in ISO 23704-1, ISO 23704-2, ISO/ASTM 52900, and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

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— IEC Electropedia: available at https://www.electropedia.org/

3.1 Terms, definitions and abbreviations

3.1.1
additive manufacturing component
AM component
single piece or group of pieces forming a functional unit within an additive manufacturing (AM) machine *unit* (3.1.15)

3.1.2
additive manufacturing function
AM function
function performed by an additive manufacturing (AM) machine *unit* (3.1.15) instance

3.1.3
additive manufacturing machine unit
AM machine unit
AMU
instance of a cyber-physically controlled machine tool (CPCM) for additive manufacturing (AM) in the reference architecture of cyber-physically controlled smart machine tool systems (CPSMT) for AM

3.1.4
additive manufacturing process
AM process
process of joining materials to make a part from a 3D model data layer by layer in the reference architecture of a cyber-physically controlled machine tool (CPCM) for additive manufacturing (AM)

Note 1 to entry: Definition is based on the ISO/ASTM 52900 definition of single-step AM process in Annex B.

3.1.5
additive manufacturing workflow
AM workflow
sequence of process steps involved in producing a physical part using additive manufacturing

Note 1 to entry: The AM workflow consists of a) product design, b) feedstock, c) build preparation, d) process control, e) post-processing, f) quality control, and g) part.

3.1.6
build motion
machine movements needed for creating a product with feedstock / support

Note 1 to entry: Feedstock and support are defined in ISO/ASTM 52900 in the context of additive manufacturing.

3.1.7
build process
realization of the material joining by providing a source of activation

Note 1 to entry: Joining means realization of consolidation of the raw material to create the final form using a material activation method.

Note 2 to entry: Example activation methods are binding mechanism, chemical reaction or heating.

3.1.8
cyber physical system unit
CPS unit

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Deleted: 1) Product
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Deleted: 4) Process
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collection of functional entities responsible for advanced cyber-physical control

Note 1 to entry: ISO 23704-1:2022, 3.1.8 defines a CPS (Cyber-Physical System) as a physical and engineered system whose operations are monitored, coordinated, controlled and integrated by a computing and communication core.

Note 2 to entry: The CPS unit provides advanced control functionalities for the *machine tool unit* (3.1.13), interfacing with data from sensors, numerical control kernel / programmable logic controller, the cyber-supporting system for machine tool (CSSM), shop floor control system (SFCS), and unified interface system (UIS).

3.1.9
cyber-physically controlled smart additive manufacturing system
CPSAM
smart additive manufacturing system (SAMS) (3.1.14) viewed from the capabilities of cyber-physically controlled smart machine tool systems (CPSMT)

Note 1 to entry: See ISO 23704-1:2022, Clause 10 for the capabilities of CPSMT.

3.1.10
digital thread
framework that provides an integrated view of all data throughout the *AM workflow* (3.1.5)

Note 1 to entry: The digital thread manages a record of a product from its creation to its removal. The CAx chain (CAD, CAPP, CAE, CAM, CNC, CMM) is a key enabler for this, based on[103].

Note 2 to entry: The data are interconnected in a series of feedback and feedforward loops.

Note 3 to entry. For more details on digital thread including the difference between digital thread and digital twin, see Annex B.

3.1.11
digital thread unit
instance of a *digital thread* (3.1.10), focussed on the operation phase, in the reference architecture of cyber-physically controlled smart machine tool systems (CPSMT) for additive manufacturing (AM)

3.1.12
feedstock / support handling
delivery (feeding), storage and management of the remaining feedstock / support on the machine, e.g. recoating and surface leveling mechanism in vat photopolymerization, powder feeding system in binder jetting

3.1.13
machine tool unit
unit (3.1.15) consisting of hardware that performs a series of machine tool functions

Note 1 to entry: According to ISO 14955-1, the machine tool function consists of machine tool operations (machining process, motion and control), process conditioning, *workpiece* (3.1.16) handling, tool handling or die change, recyclables and waste handling and machine tool cooling / heating.

3.1.14
smart additive manufacturing system
SAMS
additive manufacturing system that supports the vision, characteristics, and capabilities of smart manufacturing

Note 1 to entry: Details of smart manufacturing are described in IEC TR 63319[49].

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3.1.15
unit
group of elements that constitutes part of the reference architecture of a cyber-physically controlled machine tool (CPCM) and a cyber-supporting system for machine tool (CSSM) for additive manufacturing

Note 1 to entry: The term “unit” here is used as an instance of a collection of elements.

3.1.16
workpiece
joined material forming a functional element that could constitute all or a section of an intended product

Note 1 to entry: The functional requirements for a workpiece are typically determined by the intended application.

[SOURCE: ISO/ASTM 52900:2021, 3.9.1, modified — term “part” changed to workpiece]

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3.2 Symbols and abbreviated terms

For the purposes of this document, the abbreviated terms given in ISO 23704-1, ISO 23704-2, and the following apply.

AM	Additive Manufacturing
AMF	Additive Manufacturing File Format
CPCM	Cyber-Physically Controlled Machine tool system
CPS	Cyber-Physical System
CPSAM	Cyber-Physically controlled Smart Additive Manufacturing system
CPSMT	Cyber Physically controlled Smart Machine Tool system
CSSM	Cyber Supporting System for Machine tool
KPI	Key Performance Indicator
SAMS	Smart Additive Manufacturing System
SFCS	Shop Floor Control System
SFDS	Shop Floor Device System
STL	Standard Transformation Language
3MF	3D Manufacturing Format
UIS	Unified Interface System

4 Conformance with the CPSMT reference architecture for additive manufacturing (AM)

To claim conformance, a definition of specific system architecture provided by a vendor or system integrator should use the terminology, architectural concepts, and have the capabilities defined in this document, within the scope of their specific use cases.

5 Goals and objectives of the CPSMT reference architecture for AM

The CPSMT reference architecture for AM describes an architecture of smart machine tool systems for AM based on the generic reference architecture specified in ISO 23704-1. It provides guidance for designers developing smart machine tool systems for AM and aims to give a better understanding of smart machine tools to the stakeholders of such systems.

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NOTE Examples of stakeholders are machine tool builders, CNC vendors, solution vendors, service providers, customers and end-users.

The CPSMT reference architecture for AM ensures the following important standardization objectives:

— transparent and unambiguous communication between all interested parties of an SAMS,

— the interoperability of an SAMS with related hardware devices, software, services, and manufacturing systems,

— the quality / capability of an SAMS,

— the use of an SAMS, and

— systematic development, modification of an SAMS.

Figure 2 illustrates the context of how the CPSMT reference architecture for AM is derived and viewed from various perspectives.

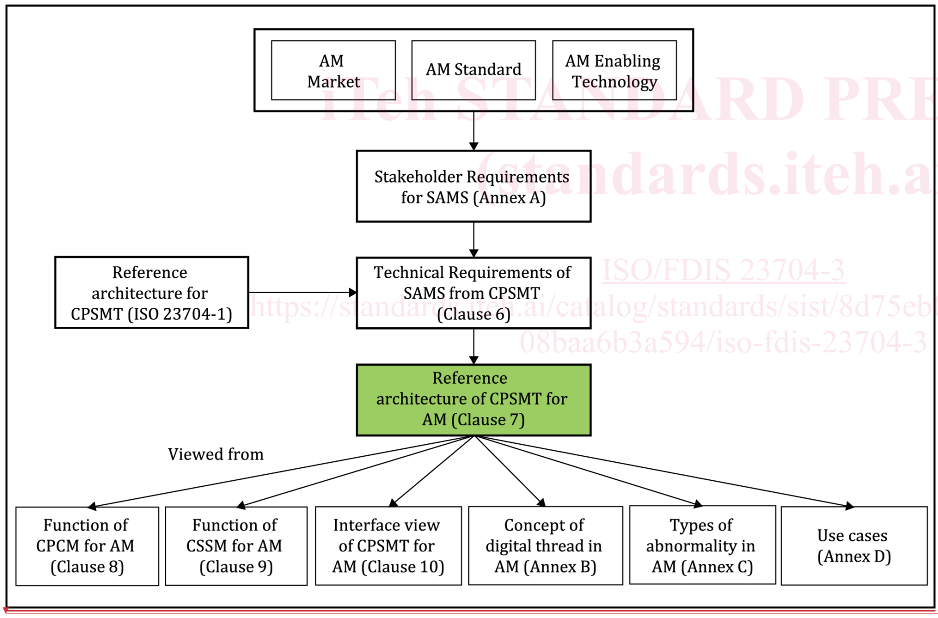

Figure 2 — Context of the CPSMT reference architecture for additive manufacturing (AM)

Based on Figure 2, this document has the following descriptions:

— The technical requirements of an SAMS from the CPSMT perspective in Clause 6,

— The reference architecture of a CPSMT for AM in Clause 7,

— The reference architecture of a CPCM for AM viewed from a functionality perspective in Clause 8,

— The reference architecture of a CSSM for AM viewed from a functionality perspective in Clause 9,

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- The reference architecture of a CPSMT for AM viewed from the interface perspective in Clause 10,
- The stakeholder requirements on an SAMS in Annex A,
- The concept of digital thread in AM in Annex B,
- The types of abnormality in AM in Annex C, and
- Example use cases on the reference architecture of a CPSMT for AM in Annex D.

6 Technical requirements of a smart additive manufacturing system (SAMS) from the CPSMT perspective

6.1 General

This Clause describes the technical requirements of the SAMS mainly based on the AM stakeholder requirements described in Annex A from the perspective of a CPSMT as summarized in Table 1.

NOTE 1 In the view of 'systems engineering,' an advanced methodology for developing complex systems, the technical requirements described in Clause 6 correspond to 'system requirements,' the technical requirements to be satisfied by the reference (solution) architecture for the smart manufacturing system are specified in Clause 7.

NOTE 2 For details on systems engineering, see ISO/IEC/IEEE 15288, ISO/IEC/IEEE 12207, ISO/IEC/IEEE 42010.

In terms of the phase of the AM workflow, the technical requirements are functions to be fulfilled by the SAMS during the process control (operation) phase categorized into six capabilities of a CPSMT specified in ISO 23704-1:2022, Clause 10.

NOTE 3 The 'life cycle aspect' defined in ISO 23704-1 corresponds to 'AM workflow' in the AM domain.

The details of the technical requirements in each category are given in the following subclauses so that they can be used as the requirements to be satisfied by the reference architecture of a CPSMT for AM specified in Clause 7.

Table 1 — Technical requirements of Smart Additive Manufacturing System (SAMS) from the CPSMT capabilities

Categories based on the CPSMT capabilities (subclause number in this document)	Technical requirements (subclause number in this document)
Autonomous dealing with abnormalities (6.2)	6.2.2 Dealing with hard real-time scale abnormalities during an AM process
	6.2.3 Dealing with soft real-time scale abnormalities during an AM process
	6.2.4 Acquisition of data related to an AM process
	6.2.5 Data processing related to an AM process
	6.2.6 Extraction of value-added data
	6.2.7 AM process monitoring
	6.2.8 AM process status prediction
	6.2.9 AM process status diagnosis
	6.2.10 Making decisions about the AM system to enhance AM process performance

	6.2.11 Update of AM workflow data
	6.2.12 Dealing with abnormalities
Autonomous coordination with shop floor devices (6.3)	6.3.2 Coordination among shop floor devices
	6.3.2 Supporting the combination of finish cutting in subtractive manufacturing and AM process
Autonomous collaboration with shop floor control system (6.4)	6.4.2 Receiving a coordinated process plan
	6.4.3 Providing the AM process data for shop floor operation
	6.4.4 Interoperability for the data interface
Interface with an AM workflow (6.5)	6.5.2 Interaction with AM workflow
	6.5.3 Interoperability for interface with AM workflow
Interface with hierarchy level (6.6)	6.6.2 Interaction with a hierarchy level
	6.6.3 Interoperability for interface with hierarchy level
Interface with humans (6.7)	6.7.2 Interaction with humans
	6.7.3 Interoperability for interface with humans

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6.2 Technical requirements of autonomously dealing with abnormalities

6.2.1 General

This subclause describes the technical requirements of an SAMS from the "autonomously dealing with abnormalities" capability perspective.

NOTE 1 See ISO 23704-1:2022, 3.1.1 for the definition of abnormality.

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NOTE 2 As noted in ISO 23704-1:2022, 10.1, the capability of dealing with abnormalities is emphasized due to the fact that:

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— In principle, total optimization of the manufacturing process, in essence, is done by: a) off-line optimization (e.g. via CAx, DfAM), followed by b) on-line 'faithful' execution.

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— Faithful execution can be done by autonomously dealing with abnormalities; the deviations from the normal status optimally planned off-line.

6.2.2 Dealing with hard real-time scale abnormalities during an AM process

This technical requirement means dealing with abnormalities during the AM process in a hard real-time fashion. Hard real-time means the result of data handling is incorrect unless the measure meets the specified timing requirements.

NOTE 1 See ISO 23704-1:2022, 3.1.17 for the definition of hard real-time.

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NOTE 2 Hard-real time does not mean the process itself, but the controller task, i.e. even a slow process is operational in real time.

There are abnormalities occurring abruptly during the build process, e.g. within a layer, between layers, immediately adversely affecting the AM system when measures are not taken within the time limit. In order to detect and take action for these abnormalities, the AM process needs to be checked and handled in hard real-time.

Explicitly, an SAMS should have a means for dealing with the abnormalities in a hard real-time scale.

NOTE 3 Example abnormalities to be dealt with in the hard real-time scale include inappropriate melt pool geometry and thermal distribution, servo disturbance, clogging.

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