Digital Twin
System Interoperability Framework

A Digital Twin Consortium Whitepaper

2021-12-07

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Section 1 – Introduction

Interoperable Systems Empower Digital Twins

Providing virtual representations of real-world entities and processes, emerging digital twin systems offer the opportunity to study the virtual and the physical either separately or together. For businesses, this powerful possibility holds the key to accelerating holistic understanding and improved decision-making through human and artificial intelligence.

Digital twins produce actionable information, feed verifiable artificial intelligence systems, and are used to improve strategic, design, operational, and maintenance decisions of both real and virtual systems. In doing so, they depend on interoperable frameworks that enable the processing of heterogeneous information from heterogenous systems.

Paper Objectives

- To provide a framework for unifying a nascent ecosystem of high-value, multi-vendor services that can seamlessly "plug into" a multi-dimensional, interoperable system of systems.
- To characterize a dynamic and scalable framework for interoperable and interchangeable systems that empowers the digital twin system-of-systems.
- To align existing interoperability initiatives around a common system-centric framework for scalable interoperability mechanisms.
- To support all cross-domain information sets feeding into a digital thread.
- To support all phases of a product life cycle and maximize the value of a digital twin and the asset it represents.
- To simplify, through abstraction, the required core mechanisms for scaling adoption of the digital and subsequent physical twin, where a physical twin can be a cyber-physical (IoT) system.
- To enable the reduction of costs required to integrate systems, without which implementation remains cost-prohibitive for many use cases.
- To minimize effort in preparing and normalizing data for consumption – processes which can account for the majority of data scientists' work.

Scope of Systems in this Framework

The authors would like to thank and acknowledge the many contributors and reviewers of this paper. Trying to define the characteristics of universal system interoperability has its challenges. Namely, it requires a high degree of abstract thinking.

The authors believe that this task is worthy of the effort. The concept of digital twins, taken to its ultimate potential, can create digital representations of everything. Yet, much of the value of digital twins depends on the ability of distributed, heterogeneous systems to interoperate.

Many subject matter experts have commented on the definition of a system. The authors understand some experts may have varying viewpoints about system characteristics, behavior, and interoperability within specific domains.

To accommodate all domain-specific viewpoints requires an overarching abstract viewpoint incorporating general concepts applicable to all use cases. In this higher-level view, the authors assert that everything represented by a digital twin can be modeled as a system.

This paper frames the design considerations necessary to make these modeled systems interoperate at scale. Reference architectures that properly address these considerations can unify ecosystems of high-value, interoperable systems-of-systems.

We invite the reader to be open to this abstract perspective by considering everything as systems and envisioning a digital world where these systems can inherently interoperate and enable digital twin systems to realize their full potential.

Conventions

The first use of a Glossary term is underlined.

Key Digital Twin Concepts

An interoperability framework needs to consider both asset-centric and system-centric viewpoints, as well as the relationships between the two. To support the correlation of heterogeneous information sets, an interoperability mechanism needs to couple an asset-centric digital thread with a system-centric system-of-systems.

Digital Thread

A digital thread acts as a conduit for correlating information across multiple dimensions of digital twins, spanning time and lifecycle. Digital threads are created to provide a holistic view of an asset from multiple, heterogeneous perspectives.

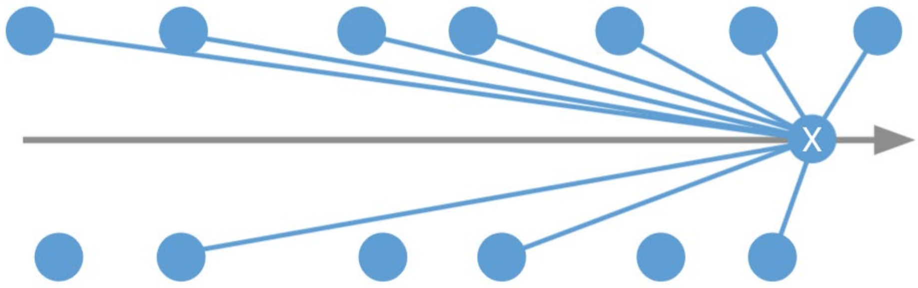

Figure 1: Depiction of a digital thread representing system X interconnected to multiple systems over time

System-of-Systems

A system of systems (SoS) is a set of distributed, autonomous, and heterogeneous systems that collaborate to achieve a common goal.

“The true potential of the internet of things and artificial intelligence can be unlocked when they come together as one complete, interdependent ecosystem…where every node is additive to the collective intelligence of the whole. We see this as the next evolutionary step in computing, one which will have a profound impact on business, industry, society, and all organizations around the world.” – Michael Dell.

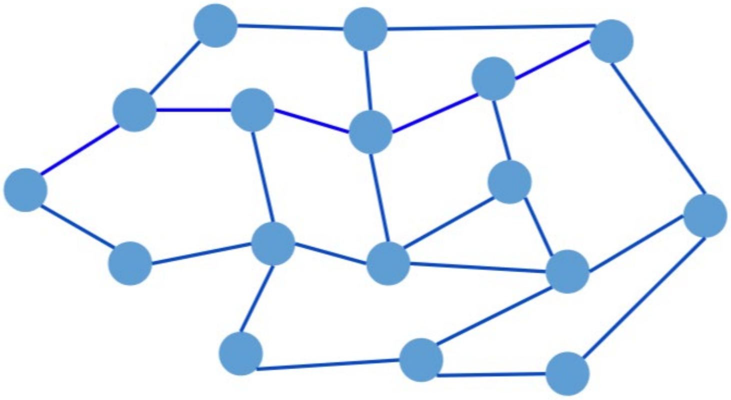

Figure 2: Depiction of systems interconnecting to create a system of systems

Aligning Consortia Initiatives

To realize the true potential of IoT and digital twins, industry consortia must properly align their data models, ontology concepts, and terminology. In doing so, they must deploy a common scalable mechanism for interoperability and distributed state management.

Consortia can accelerate the adoption of a common mechanism by abstracting and decomposing their disparate data models, and by considering the seven key concepts of a system interoperability framework.

Section 2 - Seven Interoperability Concepts

The many characteristics of this System Interoperability Framework are best considered by organizing them into seven key concepts as depicted below. Considered collectively, these concepts can guide the abstraction and decomposition of distributed system architectures into a simple common interoperability mechanism that scales to a complete, interdependent ecosystem of digital twins and high-value services.

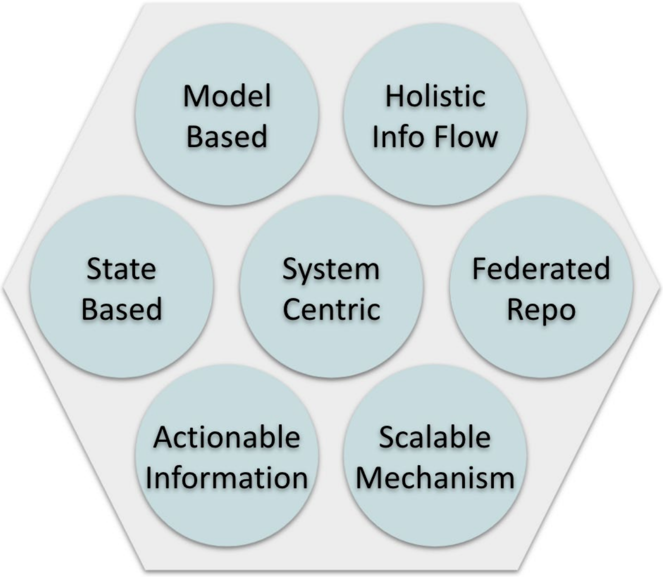

Figure 3: Seven key concepts of a system interoperability framework

A **system-centric** viewpoint normalizes **model-based** simulations of real-world entities and how they interact as a functional group within an <u>environment</u> - empowering simulation and computation to continuously optimize real-world <u>processes</u> for optimal outcomes.

This simplification can evolve a **scalable mechanism** that supports the **holistic flow** of **actionable information** produced and consumed by **state-based** systems and accessible via **federated repositories**. A multi-level system of systems based on these Framework concepts can enable holistic understanding, optimal decision-making, and effective action for humans.

1 - System-Centric Design

The rapidly growing complexity of products presents a significant challenge for manufacturers that are competing to bring the latest, sophisticated and connected products to market. This level of complexity has also introduced the need to take a systems-level approach. Such an approach enables collaboration across and within disciplines—mechanical, electronic, and software—thus creating systems of systems within a domain as well as across multiple domains. System-centric design can normalize processes, align teams, master product complexity, and drive innovation.

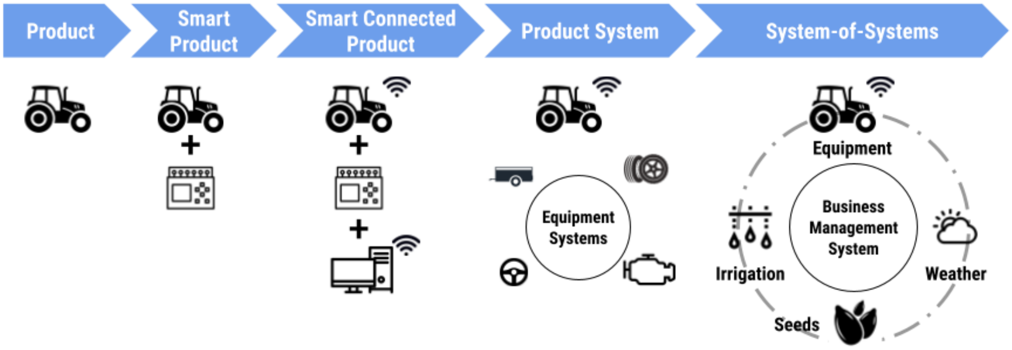

Figure 4: Transforming products into interoperable system-of-systems

“A unified system-centric framework can model businesses, smart products, and humans as systems and subsystems that can connect and interact in real-time, forming a complete, interdependent, and interoperable ecosystem. Each constituent system can be defined as independently operable but can be connected for a period of time to achieve a certain higher goal.” - Jamshidi, M., Systems of Systems Engineering: Principle and Applications, CRC Press, 2009.

Everything is a System

A system is any group of interacting or interrelated entities that act according to a set of rules to form a unified whole. A system, surrounded and influenced by its environment, is described by its boundaries, structure, and purpose, and expressed in its functioning.

> A key tenet of this Interoperability Framework is that all entities requiring interoperability (including assets) need to be viewed and represented as systems. When everything is viewed as a system, processes can be normalized and modeled via a common metamodel that is coupled to a common interoperability mechanism.

When all systems share a common metamodel for encapsulating internal behaviors, capabilities, and purpose, they become inherently interoperable, and the composability of these interconnected systems produces a System-of-Systems created for some specific purpose or value.

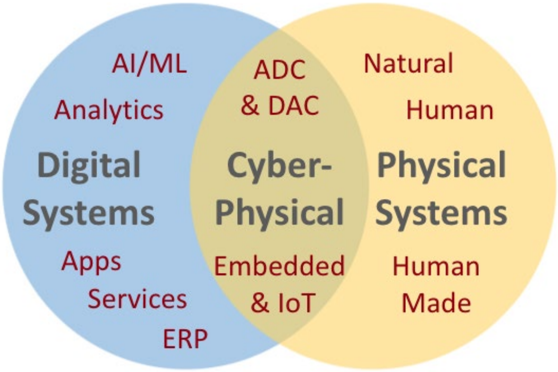

Figure 5: Types of systems representing Everything

Digital Systems

Businesses and organizations of all sizes implement digital systems to efficiently and accurately control their operations. Each of these systems incorporates computing elements coupled to an ontology or data model to manage, process, and store information objects.

Examples of digital systems include artificial intelligence (AI), machine learning (ML) and analytics engines, applications, services, and ERP systems.

Cyber-Physical Systems

Cyber-physical systems provide a key interface between digital and physical systems, encompassing analog-to-digital / digital-to-analog converters (ADC/DAC), embedded and Internet of Things (IoT) systems.

A cyber-physical system is “a type of system that integrates computing elements with the physical components and processes. The computing elements coordinate and communicate with sensors, which monitor cyber and physical indicators, and actuators, which modify the cyber and physical environment. Cyber-physical systems use sensors to connect all distributed intelligence in the environment to gain a deeper knowledge of the environment, which enables more accurate actions.” - Dr. Naoufel Boulila, Cyber-Physical Systems

Physical Systems

Physical systems are those systems found and created by nature, including human systems and human-made systems.

The human body, when also viewed as a system, is a collective processing unit comprising several organs acting as subsystems. These subsystems work in coordination with one another. Subsystems cannot work alone because there are certain needs of every subsystem that need to be fulfilled and the subsystem itself cannot fulfill those needs. All subsystems of the human body system need to support each other to perform the processes. The state of this system hierarchy can be represented digitally in the same manner that an IoT device can be represented by a “digital twin”.

Simplicity is Everything

By viewing everything that needs to interoperate as a system, everything becomes simply composable and connectable into dynamic, multi-level, systems of systems.

Composable

All entities (systems) are inherently composable to create digital threads and system-of-systems that are critical to digital twins. Systems are composed of components organized to achieve the desired purpose. System composition can be made up of discrete entities as well as subsystems.

Connectable

Our focus is to create a framework for systems to interoperate with each other. As such, the only types of entities that are of concern to this framework must be considered as systems, and the only interconnections of concern are those between systems.

Dynamic

The manner that systems connect with each other can be stable and unchanging over time (such as equipment in a building) or can be constantly changing and dynamic (such as cars crossing a toll).

Multi-Level

All systems can comprise subsystems, and each subsystem can comprise its own subsystems, forming a multi-level system of systems.

2 - Model-Based Approach

Conceptual models are critical to understanding systems, including their structures and behavior and how they interoperate with other systems. The modeling medium for digital twins is primarily digital but can also incorporate diagrams for visual representations. Common models simplify interoperability.

In a world where millions and billions of interconnections are implemented daily in dynamic ways, such models should be codified, standardized, and identified in a manner that is reusable in different use cases encountered in the field.

Goal-Oriented Models

Goals are objectives that a system should achieve through the interactions of actors in its intended environment. Digital twin systems can optimize decision-making by modeling the goals that produce the desired business outcomes.

Digital and Physics-based Models

Models can describe the structures and behaviors of both digital and physical systems.

Structures

The structures of a system can be physical (e.g., device, human), digital (e.g., microservice, API, data), or logical (e.g., organizational system, business unit, work center) and can be composed of components.

Behaviors

The behaviors of a system are based on its activities and states.

Information Models

Modeling information allows practitioners to create standard models for the elemental building blocks of systems and smart machines to drive greater modularity, extensibility, and re-use.

Atomic Data Entity

The key to modeling information for universal interoperability is to incorporate an atomic data entity as the smallest possible unit of information. An atomic data entity can provide a "lowest common denominator" for distribution of statements of fact, irrespective of knowledge domain or use case.

Simulation Models

Simulation models (e.g., discrete-event simulation) can iteratively refine themselves by considering expanded information sets to explain and predict real-world outcomes - extended to the science of Uncertainty Quantification.

Messaging Models

The method of sending and receiving messages between systems differs according to the messaging model. Instead of the traditional “pull”-based synchronous request/response or client/server interaction models, a real-time system can incorporate a pub/sub model to “push” notifications out to connected systems, in a unidirectional, asynchronous pattern. Changes to each connected system can be deployed more independently (and thus more frequently) with minimal impact to other systems, due to the overall reduced dependencies. Messaging models should be agnostic to communication protocols.

Connection Models

In much of computing today, a “connection” is most often thought of as the communication between endpoints, a way of transferring data between them. This Framework posits that connections represent relationships between systems - relationships where value is being realized and must be modeled.

Scalable and easy-to-implement connections between systems, a key objective of this Framework, are always made to achieve some result necessary by the overarching system. There is always a reason why system A needs to connect and exchange information with system B.

This “reason for connection” must be modeled in a manner so that any occurrences of such interconnection between any systems should be able to be accomplished by simply instantiating the model that is most suitable for the necessary connection. All the communication parameters, messaging formats, meaning, protocols, access, and security criteria should be accommodated in such models.

The information that travels across connections, often referred to as “messages”, should also be modeled in accordance with the requirement and purpose of the connection. These messages are often domain-specific and should be transported using semantics and ontologies specific to such domains so that the information can be easily understood by the systems serving and consuming the information.

In other words, the full mechanism for information flow between systems under this Framework must be modeled and be replicable when needed with minimal thought and effort.

Model of Models

The information that describes the model (the model’s metadata) can be considered a model-of-models or metamodel. When all systems share a common metamodel for encapsulating internal behaviors, capabilities, and purpose, they become inherently interoperable.

3 - Holistic Information Flow

A core purpose of a digital twin system is to accelerate holistic understanding of the real world for optimal decision-making, where the “world” can be a building, utility, city, country, or other environment. All information exchanged between related systems must support the broader objective of the digital twin - not just the isolated connection between two subsystems.

Cross-Domain

Information relevant to holistic understanding can originate from multiple domains and use cases. These cross-domain, heterogeneous information sets may incorporate disparate syntactic and semantic standards that must be correlated within a digital thread.

Bi-Directional

All information flow must support unidirectional and bi-directional information exchange.

While analytics applications only require a unidirectional flow of contextual events, automation systems require a bidirectional information flow to transmit measured data from sensors and command messages to actuators. A command can be structured as a contextual event to set/control an attribute value of an actuator.

Iterative

To support optimal decision-making and actions, digital twin systems require continuous and recursive process refinement through the exchange of information, including the information flow from sensing systems to artificial intelligence and machine learning systems to actuation systems (observe, analyze, act).

Lifecycle-based

Information correlated by a digital thread spans time and lifecycle. The history of information related to a digital twin is critical to holistic understanding and optimal decision-making. This information has its own lifecycle starting from origination, and continuing through transportation, storage, retrieval, and use by component systems. A digital thread must ensure the fidelity and governance of information throughout its full lifecycle.

4 - State-Based Interactions

The concept of state is fundamental to computing systems. The state of an entity (system) encompasses all the static and dynamic attribute (property) values of the entity at a point in time. The state of an entity changes, transitioning from one state to another, when triggered by an event that is internal or external to the system.

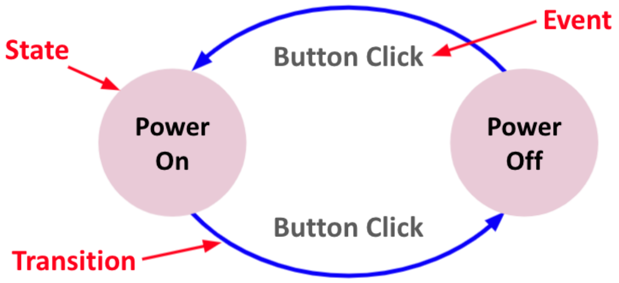

Figure 6: Interaction between State, Event, and Transition

State is Information

The declaration of each attribute value is a statement of fact about the entity, which is often represented as a state of the entity. Data representing state can be considered facts about an entity, and contextualized data can be considered information about an entity. Thus, state is considered as valuable information about an entity.

State Changes are Synchronized

State changes can be synchronized between systems through information exchange (e.g., event notifications, messaging). A computing system can persist the state of one or more entities.

The synchronization of state changes across systems often provides a very valuable way for systems to influence or be influenced by other systems enabling a coordinated and easy-to-understand systems-of-systems interoperation.

Systems are Stateful

State changes within a system often invoke a system process within the system or externally. State changes are the input and output to stateful system processes. Likewise, system processes often influence the state of the system in question or an external system when they are interconnected. As such, state changes and system processes are considered interdependent of each other.

5 - Federated Repositories

Modern computing systems are increasingly distributed. For example, product systems that many consumers would consider "discrete" (e.g., the coffee making system of a coffee machine) are often made up of many subsystems each performing a specific task supporting the product's goals. Engineered systems such as buildings and other non-repeating assemblies of components comprise a federation of systems that are interconnected for a specific goal. In all of these cases of distributed systems, information persists everywhere.

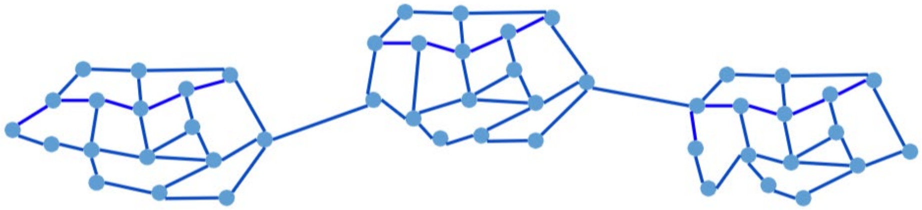

Figure 7: A Depiction of a federation of systems

Distributed

Persisted information is inherently distributed among multiple systems.

Distributed repositories of information must also be agnostic to the location of information storage, such that any specific information set can be stored on an edge device, cloud storage, distributed ledgers, and any other storage technologies relevant to the needs of the system components. Differing storage technologies have specific features and limitations which should be considered in the design of the system and its components.

Heterogeneous

A large and complex digital twin system will likely include entities pertaining to multiple domains, each with its own semantics. Persistent information in such systems will contain domain-specific information from multiple and heterogeneous subsystems.

Heterogeneous information sets will inherently incorporate disparate syntactic and semantic standards, both of which must be accommodated for system interoperability.

This necessitates translators and gateways so that information from different and incompatible domains can be normalized when needed for holistic knowledge.

Accessible

Information access must always be security managed.

6 - Actionable Information

A key objective for this Framework is to evolve a common interoperability mechanism, where one system can simply consume and react to information from another system, and where each system is additive to the collective intelligence of the whole.

To provide value to the holistic system, information exchanged between any component systems must have the characteristics that enable effective action.

Contextual

Semantic interoperability enables systems to interpret meaning from structured data in a contextual manner. Semantic interoperability relies on ontology-based “contextual metadata” supplementing “data” to form “information” exchanged among connected systems. This ontology must account for metadata exchanged between disparate systems and environments. It represents the highest level of interoperability between connected systems - beyond syntactic interoperability.

Trusted & Secure

Trust can be defined as the degree of confidence that a system performs as expected. Trust must be communicated between systems in a consistent and normalized manner regardless of the type of system or information being exchanged. Characteristics of trust include safety, security, privacy, reliability, and resilience.

A security framework must protect the information exchanged among the systems in an SoS, while preserving system autonomy and interoperability. Confidentiality and integrity of information can be protected by combining context-aware access control with trust management.

Provenance

In complex digital twin systems, information is often passed between systems over time. The provenance (the place of origin or earliest known history) of the information is critical to ascertain the validity of any conclusions made from analyzing the information.

Identifiable information sources must hold information history for audit and analytics purposes and should be accessible at any point in time.

An Authoritative Source of Truth (ASOT) can convey provenance, where the source of information is recognized by members of a Community of Interest.

Deterministic

The frequency of information should be deterministic (predictable). The inherently complex and dynamic digital twin means that the array of systems in a twin is unpredictable from use case to use case. An interoperable mechanism must provide a range of deterministic behavior when two or more entities have an opportunity to exchange useful information.

Frequency

Systems may need to operate with other systems at an interval that can be measured in milliseconds, minutes or days. The interoperability mechanism must provide a way for parties to derive a common understanding of the timeliness of the information being exchanged.

Fidelity

Vastly different types of systems are likely to have different quality requirements for information (e.g., an MRI machine vs lighting systems). Interoperability between systems must respect this difference while providing ways for systems requiring high fidelity to demand the same from entities it interoperates with.

Valuable

The conveyance of information between systems is the conveyance of value. A mechanism for interoperation must be able to manage and monitor such flow and recognize such value, when necessary, given the relationship between the systems providing and using information.

Read-Optimized

Information should be exchanged using a format that is optimized for the recipient which may be a machine, human, or AI/ML engine. Adopting a unifying interoperability model will enable information to be aggregated, indexed, and analyzed by simulation and AI engines without prior preparation, allowing data scientists to re-allocate their time to refining algorithms.

7 - Scalable Mechanisms

To implement interoperable systems based on this Framework, the interoperability mechanism(s) must be inherently scalable from the simplest interoperation of two systems to the interoperability of a dynamic coalition of distributed, autonomous, and heterogeneous systems within a complex and global ecosystem containing millions of unique entities.

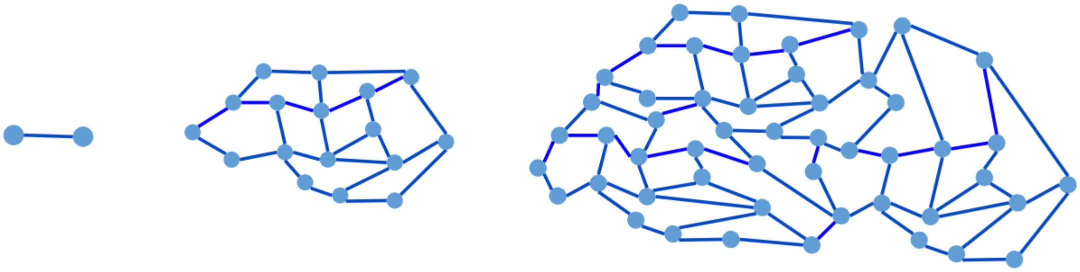

Figure 8: System interoperation must scale from simple to complex use cases

The Framework must provide the mechanisms for controlled and secure sharing of digital information, including the metadata that defines systems (e.g., digital twins) and system connections.

Simplicity of Design

To scale, the mechanism must be simple in design and implementation. Simplicity is best derived from a model-based, systems-centric design as described in this Framework.

Implementation Agnostic

The mechanism must be agnostic to communication protocols and data formats while supporting adaptors for each with minimal engineering.

Dynamic System Connections

The mechanism must allow each independently operable "constituent" system to be dynamically connected for a period of time to achieve a certain higher goal. The mechanism must automate the discovery of valuable systems and their interoperation with other systems, removing the need for human intervention in most cases.

System Discoverability

> The mechanism must provide predictable discoverability based on predefined information and use cases. Discoverability must filter high-value, compatible systems from a potentially vast number of available candidate systems.

Capability Matching

> The mechanism must match roles and capabilities of compatible systems and information flows in any given context with minimal (ideally no) human engineering interventions.

Interchangeable Systems

The mechanism should enable like-kind systems to be interchanged dynamically without affecting the system of systems' stability, performance, or the ability for other components to continue to work as expected.

Section 3 - Conclusions

Simplicity Scales

Interoperability is a core concept of computer systems and networks, denoting the ability to discover, connect, and interact with other entities within an application's broader context. In today's distributed computing paradigm, efficiently achieving interoperability at all levels of the technology stack is paramount to deriving the most benefit from a system of systems.

For decades, the focus of interoperability has been on making discrete components work in conjunction with one another. The Internet itself is perhaps the best example of billions of devices interoperating at technical and syntactic levels in a truly distributed fashion. At a smaller scale, the dynamic discoverability and capabilities matching of a simple USB is yet another example of the value created through a common interoperability mechanism. The ability to instantly use a device connected via USB with our laptops is an impressive feat of technology that we frequently take for granted.

As we discover new applications of digital twin systems for the betterment of business and society, we become increasingly aware of the importance of interoperability. Ensuring that these systems' discrete components, as well as the broader system of systems, are interoperable is essential to unlocking their larger potential with less implementation cost, less risk of failure, and less complexity at scale.

In many ways, we are striving to create a framework that would enable USB-type compatibility and ease for all systems connected to the Internet and private networks. Creating a framework to codify and normalize what for years has been relegated to the domain of "system integration" is, of course, a daunting challenge. Most systems were designed to perform specific tasks and typically do not inherently interoperate with entities outside of each system.

From the authors' viewpoint, the labor-intensive work performed by the $400B+ global system integration industry is often unnecessary. We argue that this burden may be eased by designing systems around a common framework and utilizing common mechanism(s) that enable them to interoperate just like USB devices. This would empower those working in system integration to maximize their efforts' value, designing applications that perform as intended rather than through point-to-point integrations.

This paper provides the framework for such activity, delivering on the authors' aim to characterize the multiple facets of system interoperability. Our descriptions have been distilled into seven key concepts framing the design considerations necessary to make systems interoperate at scale.

While the authors may not have contemplated all permutations of system interoperability, evaluating a digital twin perspective within the Digital Twin Consortium has provided the breadth and depth of scope necessary to address this paper's objectives.

We believe that we have created a framework capable of unlocking significant value in complex distributed computing systems such as digital twins. As we invite you to review, challenge, refine, and adopt this framework, we hope it proves useful in designing computing systems that improve our lives.

Annexes

Annex A Glossary

Aggregation

Aggregation is an integration strategy that involves copying data to gather it into a centralized location. In software architecture, aggregation implies gathering, copying, and possibly transforming information from multiple systems into a single centralized system. - *Digital Twin Consortium*

Application

An application (or app) is a computer program designed to carry out a specific task other than one relating to the operation of the computer itself, typically to be used by end-users. - *Wikipedia*

Attribute

An attribute is a characteristic or property of an entity that can be used to describe its state, appearance, or other aspects. - *ISO/IEC 24760-1:2011*

Authoritative Source of Truth (ASOT)

An authoritative source of truth is an entity such as a person, governing body, or system that applies expert judgement and rules to proclaim a digital artifact is valid and originates from a legitimate source. - *Object Management Group*

Capability

A capability (or usage capacity) is an ability to initiate, to participate in the execution of, or to consume the outcome of some tasks or functions. - *Industry IoT Consortium*

Component

A component is a modular, deployable, and replaceable part of a system that encapsulates implementation and exposes a set of interfaces. - *ISO 14813-5:2010*

Cyber-Physical System

A cyber-physical system is a type of system that integrates computing elements with the physical components and processes. The computing elements coordinate and communicate with sensors, which monitor cyber and physical indicators, and actuators, which modify the cyber and physical environment.

Cyber-Physical Systems use sensors to connect all distributed intelligence in the environment to gain a deeper knowledge of the environment, which enables more accurate actions. - Dr. Naoufel Boulila, Cyber-Physical Systems

Data

Data is content represented in a digital and formalized manner suitable for communication, storage, interpretation or processing. - *Industry IoT Consortium*, inspired by ISO/IEC 2382:2015

Data Model

A data model is a model of data that describes its structure, data types, and meaning. - *Digital Twin Consortium*

Digital Thread

A digital thread is a mechanism for correlating information across multiple dimensions of the virtual representation, where the dimensions include (but are not limited to) time or lifecycle stage (including design intent), kind-of-model, and configuration history. - *Digital Twin Consortium*

Digital Twin

A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity. - *Digital Twin Consortium*

Digital Twin System

A digital twin system is a system of systems that implements a digital twin. - *Digital Twin Consortium*

Distributed Ledger

A distributed ledger (also called a shared ledger or distributed ledger technology or DLT) is a consensus of replicated, shared, and synchronized digital data geographically spread across multiple sites, countries, or institutions. Unlike with a centralized database, there is no central administrator. – *Wikipedia*

Entity

An entity is an object that has a recognizably distinct existence. - *ISO/IEC 24760-1:2011*

Environment

An environment is the context determining the setting and circumstances of all interactions and influences with a system. - *ISO/IEC/IEEE 42010:2011*

Event

An event is an action or occurrence recognized by a digital or cyber-physical system, often originating asynchronously from the external environment, that may be handled by the system. - *Wikipedia*

Federation

Federation is an integration strategy that involves coordinated access to data repositories without making centralized copies of them. Federation only implies gathering enough centralized “index” information to use the federated systems in a coordinated manner, without copying the bulk of their data. If transformation of data is required, it is performed on-the-fly. - *Digital Twin Consortium*

Fidelity

In the fields of scientific modelling and simulation, fidelity refers to the degree to which a model or simulation reproduces the state and behavior of a real-world entity, feature or condition. Fidelity is therefore a measure of the realism of a model or simulation. - *Wikipedia*

Frequency

Synchronization Frequency is a frequency characterizing how often synchronization occurs. - *Digital Twin Consortium*

Information

Information is data that within a certain context has a particular meaning. - *Industry IoT Consortium*, inspired by ISO/IEC 2382:2015

Interoperability

Interoperability is the ability of two or more systems to exchange information and to mutually use the information that has been exchanged. - *ISO/IEC 17788:2014*

Model

A representation of some entity modeled in some medium from some modeling perspective. - *Digital Twin Consortium*

Model-Based Systems Engineering

Model-based systems engineering (MBSE) is a formalized methodology that is used to support the requirements, design, analysis, verification, and validation associated with the development of complex systems. In contrast to document-centric engineering, MBSE puts models at the center of system design. - *Software Engineering Institute*

Ontology

An ontology is a representational artefact that describes universals and certain relations among them in a domain of interest. Ontologies generally do not specify data structures or data types used to represent particular entities. - *Digital Twin Consortium*

Process

A process is a type of composition whose elements are composed into a sequence or flow of activities and interactions with the objective of carrying out certain work. - *ISO/IEC 18384-1*

Provenance

Provenance is the chronology of the ownership, custody or location of a historical object. The primary purpose of tracing the provenance of an object or entity is normally to provide contextual and circumstantial evidence for its original production or discovery, by establishing, as far as practicable, its later history, especially the sequences of its formal ownership, custody and places of storage. - *Wikipedia*

Semantic Interoperability

Semantic interoperability is a type of interoperability such that the meaning of the exchanged information can be understood by the participating systems. - *Industry IoT Consortium*

Service

A service is a distinct part of the functionality that is provided by a system through interfaces. - *ISO/IEC TR 14252:1996*

Software System

A software system is a system that consists of several separate computer programs and associated configuration files, documentation, etc., that operate together. The concept is used in the study of large and complex software because it focuses on the major components of software and their interactions. - *Wikipedia*

Stateful System

A stateful system is a system where at any point in time the value of the output(s) depends on the value of the input(s) and of an internal state. A stateful system is similar to a state machine with "memory", as the same set of input(s) can generate different output(s) depending on the previous input(s) received by the system. - *Educative*

Syntactic Interoperability

Syntactic interoperability is a type of interoperability such that the formats of the exchanged information can be understood by the participating systems. - *ISO/IEC 19941:2017*

System

A system is a group of interacting or interrelated elements that act according to a set of rules to form a unified whole. A system, surrounded and influenced by its environment, is described by its boundaries, structure, and purpose and expressed in its functioning. - *Wikipedia*

System of Systems

A system of systems is a collection of task-oriented or dedicated systems that pool their resources and capabilities together to create a new, more complex system which offers more functionality and performance than simply the sum of the constituent systems. - *Wikipedia*

Uncertainty Quantification (UQ)

Uncertainty Quantification (UQ) is the science of quantifying, characterizing, tracing, and managing uncertainty in computational and real-world systems. UQ seeks to address the problems associated with incorporating real world variability and probabilistic behavior into engineering and systems analysis. Simulations and tests answer the question: What will happen when the system is subjected to a single set of inputs? UQ expands on this question and asks: What is likely to happen when the system is subjected to a range of uncertain and variable inputs? - *Wikipedia*

Web Service

A web service is a software system designed to support interoperable machine-to-machine interaction over a network. - *W3C, Web Services Glossary*

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