Architecture Design Patterns for Digital Twin Based Systems

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Background

Prof. Tekinerdogan received his MSc degree (1994) and a PhD degree (2000) in Computer Science, both from the University of Twente, The Netherlands. From 2003 until 2008, he was a faculty member at the University of Twente, after which he joined Bilkent University until 2015. At Bilkent, he has founded and led the Bilkent Software Engineering Group, which aimed to foster research and education on software engineering in Turkey. Currently, he is a full professor and chair of the Information Technology group at Wageningen University, The Netherlands.

He has more than 25 years of experience in information technology and software/systems engineering. He is the author of more than 300 peer-reviewed scientific papers. He has been active in dozens of national and international research and consultancy projects with various large software companies, whereby he has worked as a principal researcher and leading software/system architect. Hence, he has got broad experience in software and systems engineering in different domains such as consumer electronics, enterprise systems, automotive systems, critical infrastructures, cyber-physical systems, satellite systems, defense systems, production line systems, command and control systems, physical protection systems, radar systems, smart metering systems, energy systems, and precision farming. He has a broad and in-depth background in software engineering. In parallel, he has increasingly taken a holistic systemic approach to solve real industrial problems. He has a rare perspective in software engineering systems, software engineering, software architecture, and artificial intelligence. All of these topics, he is also actively teaching. He has developed and taught around 20 different academic courses and has provided software/systems engineering courses to more than 50 companies in The Netherlands, Germany, and Turkey.

He has graduated more than 50 MSc students and supervised more than 20 PhD students. He has reviewed more than 100 national and international projects and is a regular reviewer for more than 20 international journals. He has also been very active in scientific conferences and organized more than 50 conferences/workshops on software engineering topics.

He can communicate in five languages (English, Dutch, Turkish, French, German).

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**Systems Architecture Design Pattern Catalog for Developing Digital Twins**

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**Abstract:** A digital twin is a digital replica of a physical entity to which it is remotely connected. A digital twin can provide a rich representation of the corresponding physical entity and enables sophisticated control for various purposes. Although the concept of the digital twin is largely known, designing digital twins based systems has not yet been fully explored. In practice, digital twins can be applied in different ways leading to different architectural designs. To guide the architecture design process, we provide a pattern-oriented approach for architeecting digital twin-based Internet of Things (IoT) systems. To this end, we propose a catalog of digital twin architecture design patterns that can be reused in the broad context of systems engineering. The patterns are described using the well-known documentation template and support the various phases in the systems engineering life cycle process. For illustrating the application of digital twin patterns, we adopt a case study in the agriculture and food domain.

**Keywords:** digital twins; system engineering; system architecture design; smart agriculture; internet of things; farm management systems; remote sensing and control; virtualization

Preliminaries

Systems Engineering
Systems Architecture
Internet of Things
Design Patterns
Digital Twins
Systems Architecture

Design Patterns for Digital Twins

Digital Twins
Internet of Things - Things

- “A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies”
  - ITU-T

- The Internet of Things (IoT) is the network of physical objects or "things" embedded with electronics, software, sensors, and network connectivity, which enables these objects to collect and exchange data.

- Physical Object + Controller, Sensors, and Actuators + Internet = Internet of Things
IoT Reference Architecture

- Device Layer
- Network Layer
- Session Layer
- Application Layer
- Business Layer

Management Layer

Security Layer
Digital Twin

- a digital replica of potential or actual entities (i.e., physical twin).
- It provides rich representations of the corresponding physical entity and enables sophisticated control for various purposes.
- A key characteristic of a digital twin is that it is connected to a physical entity which is typically established by the use of real-time data using sensors.
- Digital twins are made possible through the integration of various technologies such as Internet of Things, artificial intelligence, machine learning, and data science,
- which enable living digital simulation models to be created that reflect the changes of the physical counterparts.
Systems Engineering

- **Systems engineering**, a systems thinking approach, an interdisciplinary field of engineering
- that focuses on how complex engineering projects should be designed and managed;
- **holistic** view on system

- Designing, implementing, deploying and operating systems which include hardware, software and people

I. Sommerville, Software Engineering, 2000
“Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases.”

INCOSE SE Vision 2020 (INCOSE-TP-2004-004-02, Sep 2007)
Systems Engineering Lifecycle

- Concept Stage
- Development Stage
- Production Stage
- Utilization Stage
- Support Stage
- Retirement Stage
System Architecture

- **System architecture** is the fundamental organization of a system, embodied in its components, their relationships to each other and the environment, and the principles governing its design and evolution.

- An **architecture description** is a formal description and representation of a system, organized in a way that supports reasoning about the structures and behaviors of the system.

Design Patterns

- Design Patterns are reusable abstraction mechanisms that apply design principles:
  - abstraction
  - decomposition
  - encapsulation
  - information hiding
  - separation of concerns
- for recurring generic problems
- proving the best possible solution given the constraints (forces)

Diagram:
- Context
- Problem
- Solution
Describing Patterns

- **Name**  
  - meaningful name

- **Problem**  
  - statement of the intent/goal

- **Context**  
  - preconditions and the pattern's applicability

- **Forces**  
  - description of relevant forces and constraints

- **Solution**  
  - a structure

- **Example**  
  - sample application of the pattern

- **Consequences**  
  - state of the system after applying the pattern

- **Rationale**  

- **Related Patterns**  
  - static and dynamic relations to other patterns
Research Method

Domain Analysis
Multi-Case Study Research
Identification of Digital Twin Patterns
Metamodel

Systems Engineering builds System

System adopts Lifecycle Process

Lifecycle Process includes Digital Twin Based System

Digital Twin Based System has System Architecture

System Architecture has Architecture Pattern

Architecture Pattern is-a System Architecture

System Architecture Digital Twin Pattern

Digital Twin has Physical Object

Physical Object sync Digital Twin

Digital Twin Lifecycle Stage

Lifecycle Stage includes * Lifecycle Process

Life Cycle Stage used in System Architecture

System Architecture designed using Architecture Pattern

Architecture Pattern is-a Architecture
Adopted Research Method

- Domain Analysis
- Digital Twin Literature
- Case Study Requirements
- Existing Software/System Design Patterns
- Multi-Case Study Design and Analysis
- Identification and design of DT Patterns
- Domain Model
- Digital Twins
- Case Study Design and Implementation
- Digital Twin Pattern Catalog

Bedir Tekinerdogan

Architecture Design Patterns for Digital Twin Based Systems
Domain Analysis Process

- **Domain analysis** can be defined as the process of identifying, capturing, and organizing domain knowledge about the problem domain with the purpose of making it reusable when creating new systems.

- The term **domain** is defined as an area of knowledge or activity characterized by a set of concepts and terminology understood by practitioners in that area.

- Conventional domain analysis methods consist generally of the activities **Domain Scoping** and **Domain Modeling**.
Selected Set of Primary Studies


Relationships between digital object and physical object
## Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Object</td>
<td>A “real-world” artefact, e.g., a vehicle, component, product, system, model.</td>
</tr>
<tr>
<td>Virtual Object</td>
<td>A computer generated representation of the physical object.</td>
</tr>
<tr>
<td>Physical Environment</td>
<td>The measurable “real-world” environment within which the physical object exists.</td>
</tr>
<tr>
<td>Virtual Environment</td>
<td>Any number of virtual “worlds” or simulations that replicate the state of the physical environment and designed for specific use-case (s).</td>
</tr>
<tr>
<td>State</td>
<td>The current value of all parameters of either the physical or virtual object/environment.</td>
</tr>
<tr>
<td>Realization</td>
<td>The act of changing the state of the physical/virtual object/twin.</td>
</tr>
<tr>
<td>Metrology</td>
<td>The act of measuring the state of the physical/virtual object/twin.</td>
</tr>
<tr>
<td>Twinning</td>
<td>The act of synchronizing the states of the physical and virtual object/twin.</td>
</tr>
<tr>
<td>Twinning Rate</td>
<td>The rate at which twinning occurs.</td>
</tr>
<tr>
<td>Physical-to-Virtual Connection/Twinning</td>
<td>The connection from the physical to the virtual environment. Comprises of physical metrology and virtual realization stages.</td>
</tr>
<tr>
<td>Virtual-to-Physical Connection/Twinning</td>
<td>The connection from the virtual to the physical environment. Comprises of virtual metrology and physical realization stages.</td>
</tr>
</tbody>
</table>

Conceptual Model – Control System

- Sensor
- Actuator
- Comparitor
- Decision
- Physical Object

Flow:
- Sensor → Comparitor: get state
- Comparitor → Decision: provide delta
- Decision → Actuator: command
- Actuator → Physical Object: update state
Conceptual model for Control-based digital twin

- Digital Object Space
  - Digital Object
  - Digital Object Adaptor
  - Comparitor
  - Decider
  - get digital object state
  - adapt digital object state
  - delta
  - get physical object state
  - command

- Physical Object Space
  - Sensor
  - Actuator
  - Physical Object
  - measure
  - adapt

Digital Object Space
Comparitor
Decider
Sensor
Actuator
Physical Object
Digital Twin Pattern Catalog

Digital Model Pattern
Digital Generator Pattern
Digital Shadow Pattern
Digital Matching Pattern
Digital Proxy Pattern
Digital Restoration Pattern
Digital Monitor Pattern
Digital Control Pattern
Digital Autonomy Pattern
## Documentation Template

<table>
<thead>
<tr>
<th>Documentation Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>A descriptive and unique name that helps in identifying and referring to the pattern.</td>
</tr>
<tr>
<td>Lifecycle Stage</td>
<td>The lifecycle stage(s) in which the pattern can be applied.</td>
</tr>
<tr>
<td>Context</td>
<td>The situations in which the pattern may apply.</td>
</tr>
<tr>
<td>Problem</td>
<td>The problem the pattern addresses, including a discussion of its associated forces.</td>
</tr>
<tr>
<td>Solution</td>
<td>The fundamental solution principle underlying the pattern.</td>
</tr>
<tr>
<td>Structure</td>
<td>A detailed specification of the structural aspects of the pattern.</td>
</tr>
<tr>
<td>Dynamics</td>
<td>Scenarios describing the run-time behavior of the pattern.</td>
</tr>
</tbody>
</table>
Digital Model Pattern

- **Name**—Digital Model.
- **Lifecycle Stage**—Concept, Development, and Production stages.
- **Context**—A physical object needs to be manually developed based on a digital object.
- **Problem**—Based on a digital model a physical object needs to be created.
- **Solution**—The digital twin object is used as a blueprint by the human client to develop the physical object or allocate an existing digital twin. The abstract digital twin (in italic font) defines a common reusable interface that can be enhanced by concrete digital twins. Various concrete digital twin objects can be used, which can result in similar but different physical objects.
Digital Generator Pattern

- **Name**—Digital Generator.
- **Lifecycle Stage**—Concept, Development, and Production stages.
- **Context**—A physical object needs to be automatically developed based on a digital object.
- **Problem**—Based on a digital model a physical object needs to be automatically created.
- **Solution**—The digital twin object is used as a blueprint to automatically create the physical object. The client can be a human or an external object that asks the DigitalTwin object to automatically generate a PhysicalObject.
Digital Shadow Pattern

- **Name**—Digital Shadow.
- **Lifecycle Stage**—Concept, Development, and Production stages.
- **Context**—A digital twin needs to be developed for a physical object.
- **Problem**—For a given physical object a digital twin needs to be developed. Various motivations may be given for the need for digital twin but it is essential to provide a digital object that reflects the physical object.
- **Solution**—The physical object is used as a basis to create the Digital Twin. The digital twinning is based on sensor measurements by a client (external object) of one or various different physical objects.
Digital Matching Pattern

- **Name**—Digital Matching.
- **Lifecycle Stage**—Utilization, Support.
- **Context**—A physical object needs to be found that matches the digital twin.
- **Problem**—Based on a digital model a physical object needs to be found.
- **Solution**—The digital twin object is used by an external client object to find and match the physical object(s) that have similar properties as defined by the digital twin.
Digital Proxy Pattern

- **Name**—Digital Proxy
- **Lifecycle Stage**—Utilization, Support and Retirement stages.
- **Context**—A digital twin needs to act in case of a physical object.
- **Problem**—It is often inappropriate to access a physical object directly.
- **Solution**—The design pattern makes the clients of a component communicate with a representative rather than to the component itself. Introducing such a placeholder can serve many purposes, including enhanced efficiency, easier access and protection from unauthorized access. Before executing the requested service a pre-processing function can be performed by the Digital Twin. Similarly after processing the service, a post-processing function can be performed. Once the function has been performed the synchronization of the data (twinning) will be carried out. Alternatively, this could be also done in the pre-processing or post-processing functions.
Digital Restoration Pattern

- **Name**—Digital Restoration.
- **Lifecycle Stage**—Utilization and Support stages.
- **Context**—A physical object needs to be restored to its earlier state.
- **Problem**—How can a physical object’s state be captured and externalized so that the object can be restored to this state later.
- **Solution**—A digital twin of the physical object is created at given checkpoints. In case of failure the digital twin is checked and the state of the physical object is restored.
Digital Monitor Pattern

- **Name**—Digital Monitor.
- **Lifecycle Stage**—Utilization and Support stages.
- **Context**—A physical object needs to be monitored by a human being or external entity.
- **Problem**—How can a physical object’s state be perceived and viewed to support external actions.
- **Solution**—A digital twin is connected to the physical object. The digital twin monitors the physical object continuously or at given time intervals.
**Digital Control Pattern**

- **Name**—Digital Control.
- **Lifecycle Stage**—Utilization and Support stages.
- **Context**—A physical object needs to be controlled.
- **Problem**—How can a physical object’s state be perceived and changed.
- **Solution**—A digital twin is connected to the physical object. The digital twin monitors the physical object continuously or at given time intervals, and adapts the state of the physical object.
Digital Autonomy Pattern

- **Name**—Digital Autonomy.
- **Lifecycle Stage**—Utilization and Support stages.
- **Context**—A physical object needs to be automatically controlled without human intervention.
- **Problem**—How can a physical object’s state be perceived and automatically changed without human intervention.
- **Solution**—A digital twin is connected to the physical object. The digital twin monitors the physical object continuously or at given time intervals, and automatically adapts the state of the physical object.
Pattern Selection Approach

- Concept Stage
- Development Stage
- Production Stage
- Utilization Stage
- Support Stage
- Retirement Stage

Digital Model
Digital Shadow
Digital Generator

Digital Model
Digital Shadow
Digital Generator

Digital Matching
Digital Proxy
Digital Restoration
Digital Monitor
Digital Control
Digital Autonomy

Digital Proxy
Case Study
## Case Study Design

<table>
<thead>
<tr>
<th>Case Study Design Activity</th>
<th>Case Study</th>
</tr>
</thead>
</table>
| **Goal**                   | Assessing the effectiveness of the method  
 Assessing the practicality of the method |
| **Research Questions**     | RQ1. To which extent do the defined digital twin patterns support the system architecture design?  
 RQ2. How practical is the method for applying the digital twin patterns? |
| **Background and source**  | Official requirements documents  
 Project managers and system architects |
| **Data Collection**        | Indirect data collection and direct data collection through document analysis and unstructured interviews |
| **Data Analysis**          | Qualitative data analysis |
## Adopted Use Cases

<table>
<thead>
<tr>
<th>Trial/Sector</th>
<th>Use Case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arable</td>
<td>Within-field management zoning</td>
<td>This case study focuses on within field management zoning and precision farming in arable farming. Hereby with the use of sensors, connectivity, decision support tools and smart control equipment are used to capture and transmit geo-localized real-time information at low cost. The collected data from the sensors will be processed and analyzed to measure and monitor the state of the agro-environment, e.g., soil, crop and climate. Further, the data and the decision models will be combined with agro-climatic and economic models, forecasts and advices for supporting tactical decisions and operational management of technical interventions.</td>
</tr>
<tr>
<td>Dairy</td>
<td>Happy Cow</td>
<td>The case study aims to improve dairy farm productivity using 3D cow activity sensing and machine learning techniques. Using advanced sensor technology within farm management it is aimed to monitor the cow behaviors and provide predictive analytics to provide insight on heat detection and health, and thereby support in the decision-making process and recommend feasible solutions to farmers. Data is gathered at both the cow level and herd level, to understand both individual animal and herd characteristics. For different problems, different types of sensors are used which are located, for example, in the neck of the cows (more comfortable position) during daily activity. The collected data during the day is transmitted through a high-efficient, long-range wireless communication network and stored on the cloud for the data analytics and decision-making process.</td>
</tr>
<tr>
<td>Veks</td>
<td>Chain-integrated greenhouse production</td>
<td>The focus of this case study is on developing IoT-based greenhouses involving a large amount of data, physical and virtual sensors, models, and algorithms focusing on important aspects such as water and energy use efficiency, safety, and transparency, for both conventional and organic supply chain traceability systems of tomato. In this context, the chain-integrated greenhouse production use case aims to develop a decision support system (DSS) for the greenhouse tomato supply chain based on IoT technology and the digital twin concept. With an integrated approach based on standardized information, interoperability along the production chain will be increased. This in turn will support quality and safety management, improved products and processes, and a lower environmental impact.</td>
</tr>
<tr>
<td>Use Case Digital Twin Pattern</td>
<td>Within Field Management Zoning</td>
<td>Happy Cow</td>
</tr>
<tr>
<td>-------------------------------</td>
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</tr>
<tr>
<td>Digital Model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digital Generator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digital Shadow</td>
<td>Initially, a digital model is developed for the fields that are monitored. Later on these digital shadows can become digital twins and the other patterns are applied (e.g., digital monitor, digital control)</td>
<td>Initially, a digital model of a cow is developed that captures the relevant states. Later on these digital shadows can become digital twins and the other patterns are applied (e.g., digital monitor, digital control)</td>
</tr>
<tr>
<td>Digital Matching</td>
<td>The pattern can be used to support the analysis and classification of the fields based on defined properties in the digital twin</td>
<td>Properties as defined in the digital twin (e.g., for disease detection) can be used to match with cows.</td>
</tr>
<tr>
<td>Digital Proxy</td>
<td>A digital twin can be used as a proxy to provide information about the fields.</td>
<td>A digital twin can be used as a proxy to provide information about a cow.</td>
</tr>
<tr>
<td>Digital Restoration</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Digital Monitor</td>
<td>Fields can be monitored by digital twin.</td>
<td>Cows can be monitored by digital twin for various physiological data (temperature, rumen and body activity, pH level).</td>
</tr>
<tr>
<td>Digital Control</td>
<td>Based on a sophisticated data analytics decision support, yields are predicted, management zones defined and task maps prepared for farm equipment (e.g., variable application of herbicides, water and fertilizers).</td>
<td>Based on a sophisticated data analytics decision support, monitoring various physiological data (temperature, rumen and body activity, pH level), and a cloud-based server application to provide accurate information for daily operations.</td>
</tr>
</tbody>
</table>
Conclusion

- Developing **digital twin-based systems** requires a **systems engineering** approach due to its multidisciplinary nature.
- One of the essential concepts in systems design is the notion of **design patterns**.
- We have proposed a **design patterns catalog** that can be used to leverage the development of high quality digital twin-based systems.
- The design patterns catalog is based on a conceptual model of **control systems** and includes a total of **nine different design patterns** that address different problems and that can be applied to different systems engineering life cycle stages.
- The identified patterns focus on the usage stage of the systems engineering life cycle.
- The application of patterns in the concept, realization, and retirement stages was still in an early stage of development.
- In our future work we will focus on the **implementation of the presented digital twins**, and also consider multiple different case studies from multiple different systems engineering domains.
- The exploration of other domains will help to discover additional digital twin patterns and thus extend the pattern catalog.