Architecture Design Patterns for Digital Twin Based Systems

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100years 1918 — 2018

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 and experience in software engineering. In parallel, has increasingly taken a holistic systemic approach to solve real industrial problems. With this, he has ample experience in software and systems architecting, software and systems product line engineering, model-driven software engineering, aspect-oriented software engineering, global software development, systems engineering, system of systems engineering, data science, 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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sensors MDPI

Article

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 architecting 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

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Digital twins in smart farming

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Virtualization

ABSTRACT

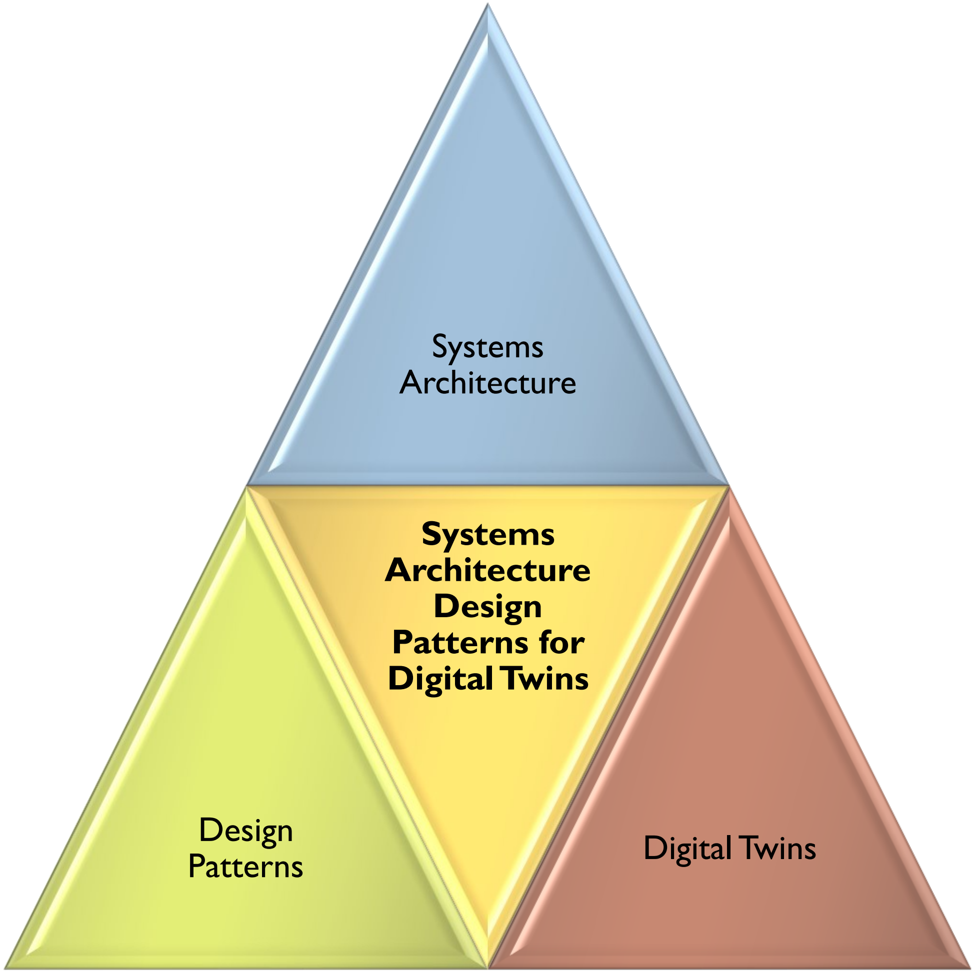
Digital Twins are very promising to bring smart farming to new levels of farming productivity and sustainability. A Digital Twin is a digital equivalent of a real-life object of which it mirrors its behaviour and states over its lifetime in a virtual space. Using Digital Twins as a central means for farm management enables the decoupling of physical flows from its planning and control. As a consequence, farmers can manage operations remotely based on (near) real-time digital information instead of having to rely on direct observation and manual tasks on-site. This allows them to act immediately in case of (expected) deviations and to simulate effects of interventions based on real-life data. This paper analyses how Digital Twins can advance smart farming. It defines the concept, develops a typology of different types of Digital Twins, and proposes a conceptual framework for designing and implementing Digital Twins. The framework comprises a control model based on a general systems approach and an implementation model for Digital Twin systems based on the Internet of Things—Architecture (IoT-A), a reference architecture for IoT systems. The framework is applied to and validated in five smart farming use cases of the European IoF2020 project, focussing on arable farming, dairy farming, greenhouse horticulture, organic vegetable farming and livestock farming.

B. Tekinerdogan and C. Verdouw. "Systems Architecture Design Pattern Catalog for Developing Digital Twins" Sensors 20, no. 18: 5103, 2020. https://doi.org/10.3390/s20185103

C. Verdouw, B. Tekinerdogan, A. Beulens, S. Wolfert, Digital twins in smart farming, Agricultural Systems, Elsevier Agricultural Systems, Volume 189, 2021, https://doi.org/10.1016/j.agsy.2020.103046

Preliminaries

Systems Engineering
Systems Architecture
Internet of Things
Design Patterns
Digital Twins

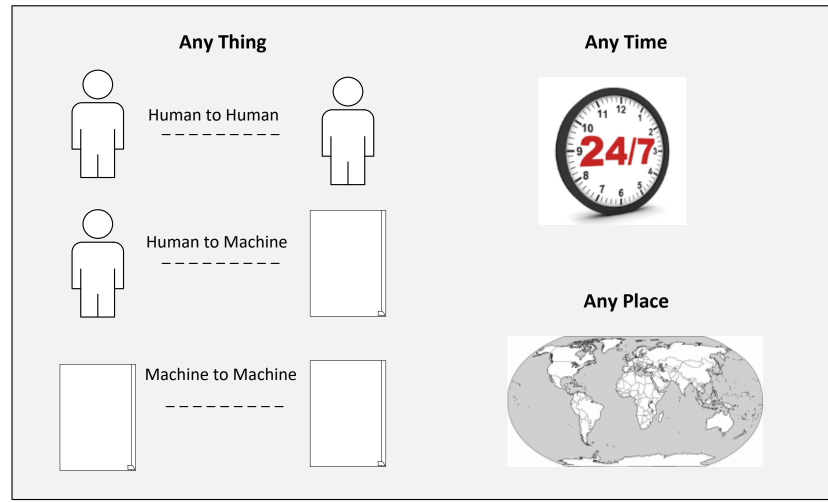

Systems Architecture
Systems Architecture Design Patterns for Digital Twins
Design Patterns
Digital Twins

Internet of Things - Things

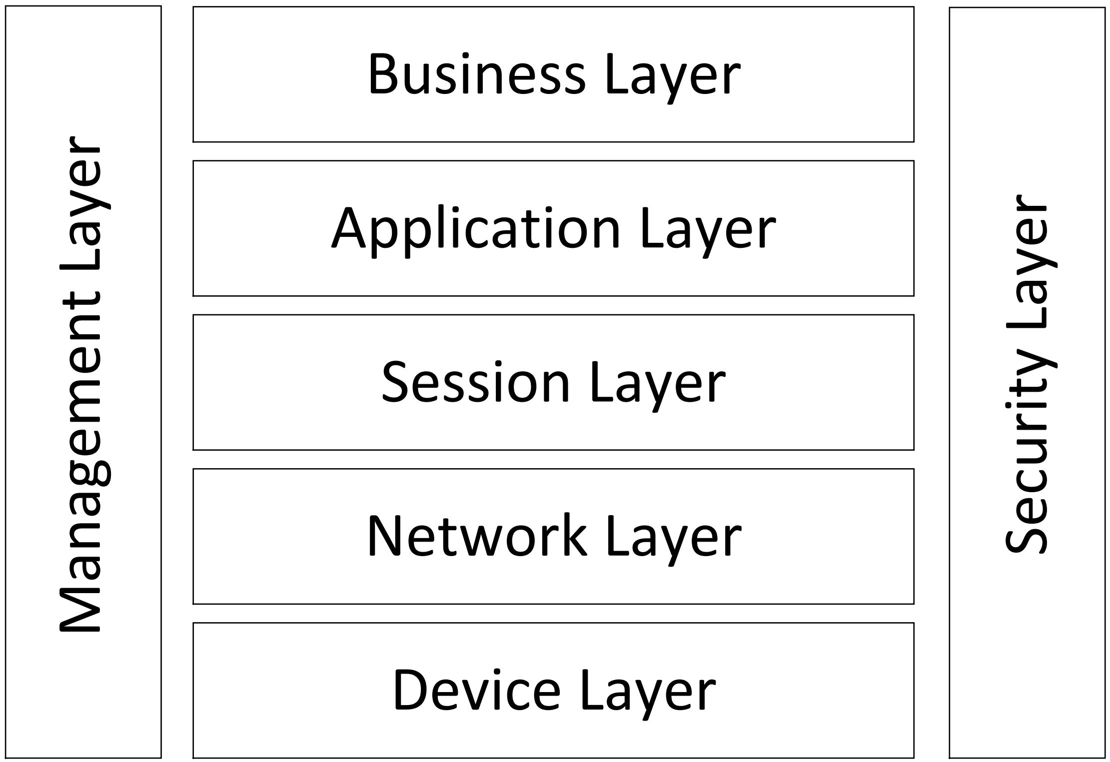
- "A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies"
  - ITU-T

- 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

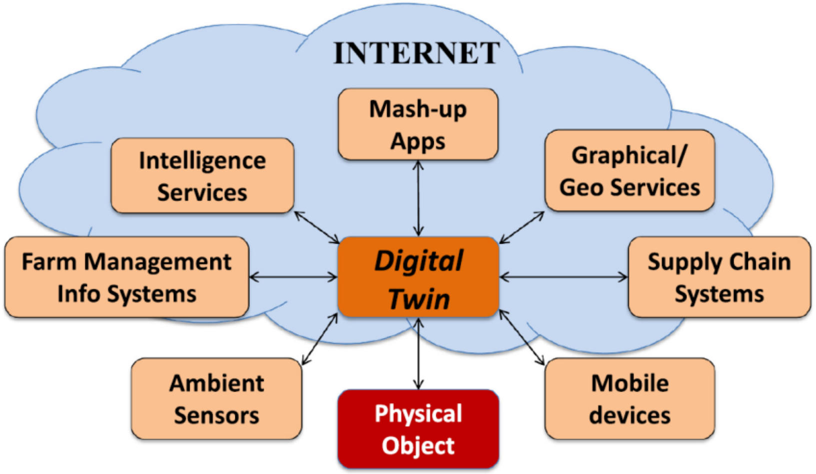


IoT Reference Architecture



Digital Twin

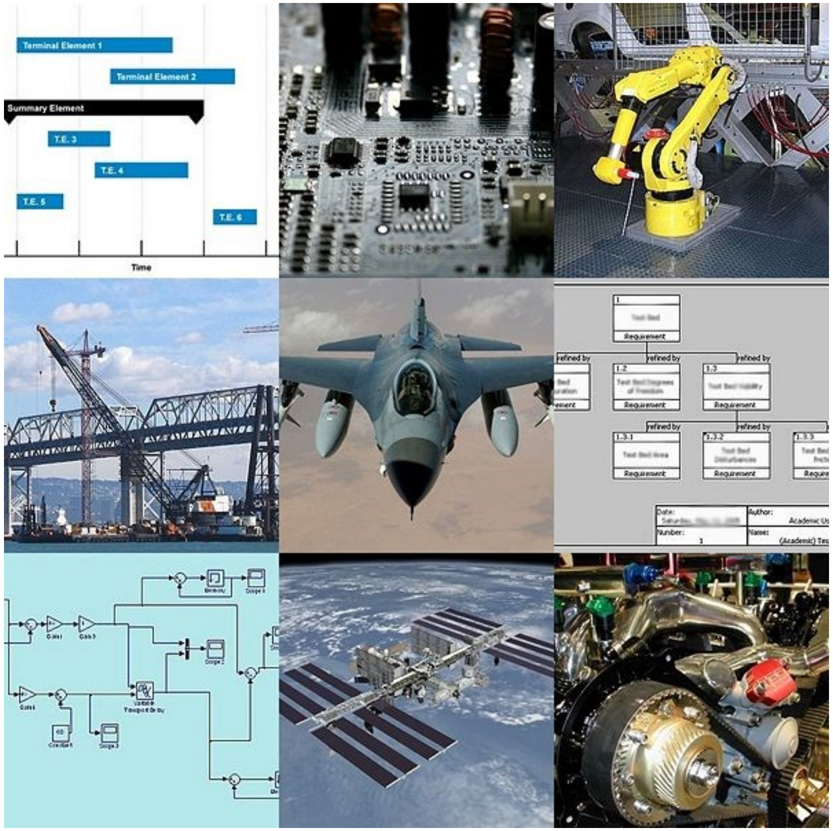
- a **digital replica** of potential or actual entities (i.e., **physical twin**).
- It provides **rich representations** of the corresponding **physical entity and enables** sophisticated control for various purposes.
- A key characteristic of a digital twin is that it is connected to a physical entity 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

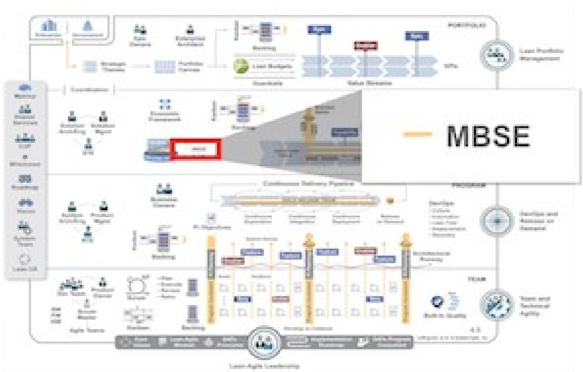


I. Sommerville, Software Engineering, 2000

Model-Based System Engineering

"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."

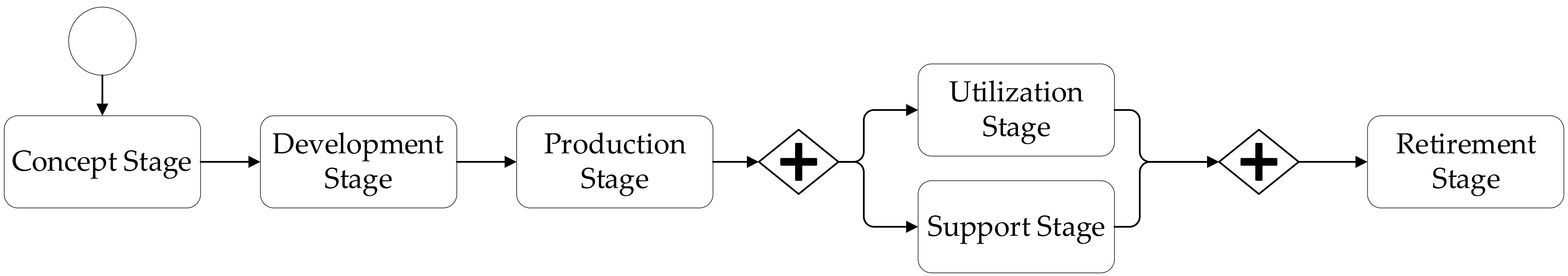
INCOSE SE Vision 2020 (INCOSE-TP-2004-004-02, Sep 2007)



Document Based

Model Based

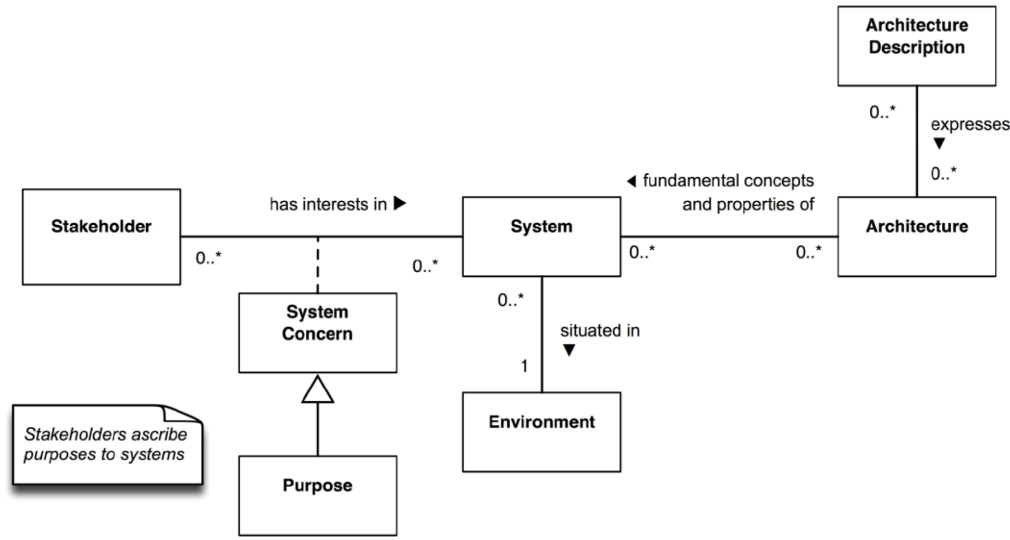
Systems Engineering Lifecycle



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.

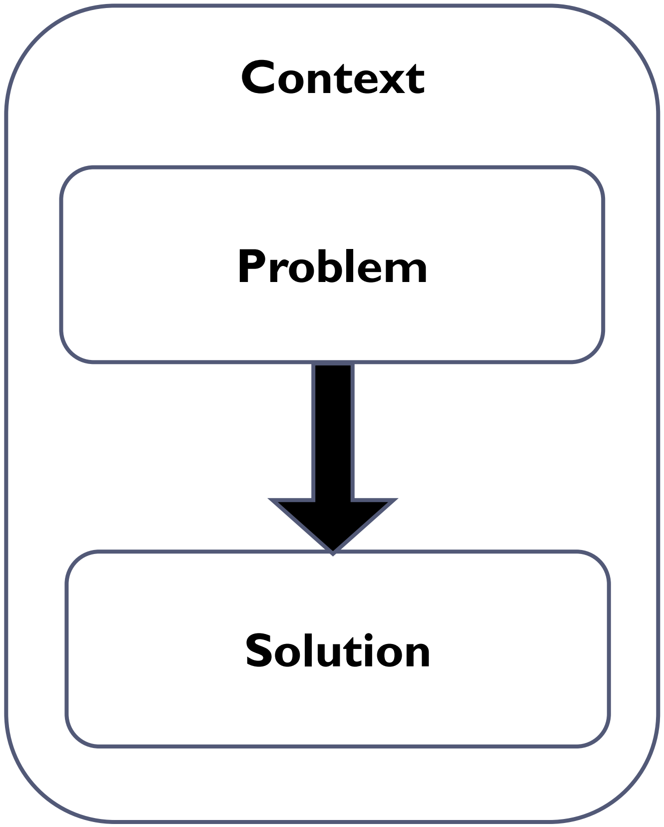
- An **architecture description** is a **formal description** and representation of a system, organized in a way that supports reasoning about the structures and behaviors of the system.



[ISO/IEC 42010:2007] Recommended practice for architectural description of software-intensive systems (ISO/IEC 42010) July 2007.

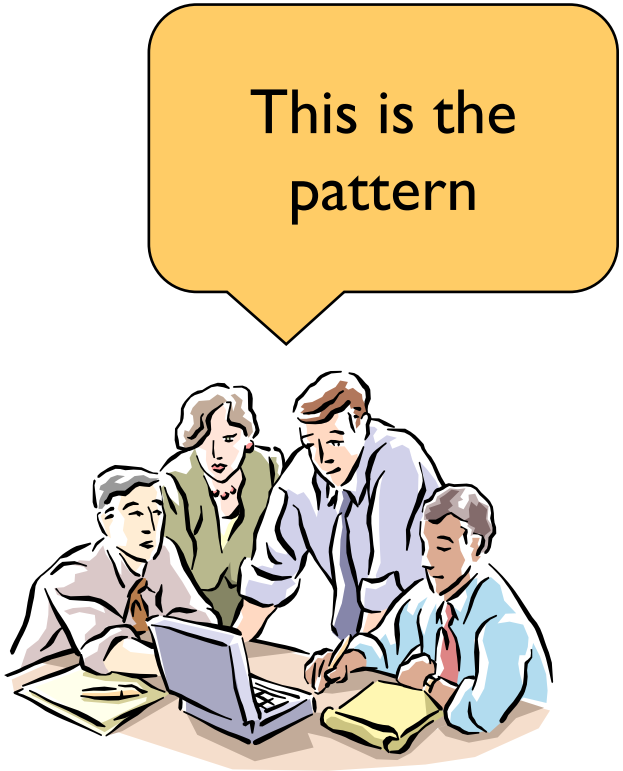
Design Patterns

- 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)



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



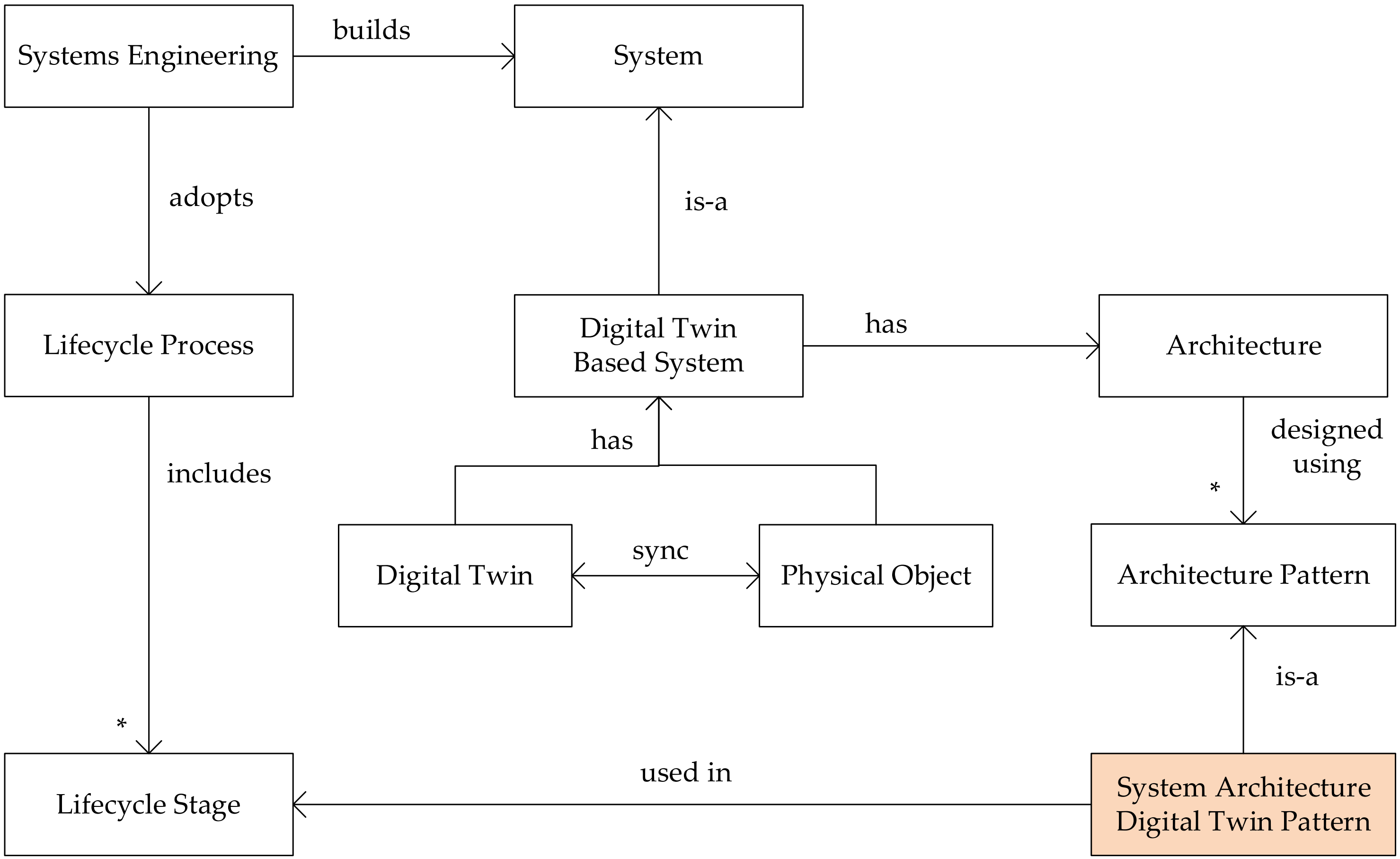
Research Method

Domain Analysis

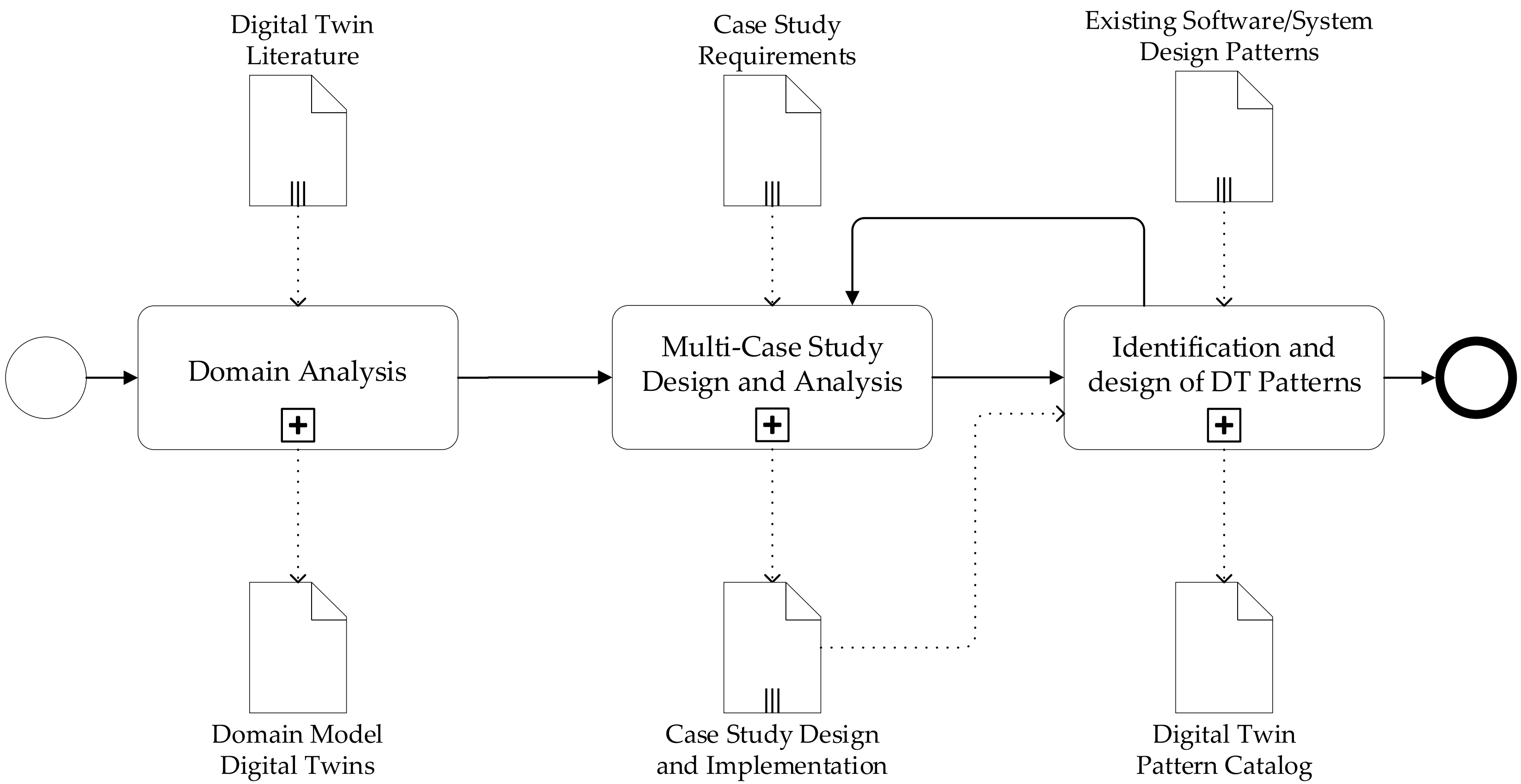
Multi-Case Study Research

Identification of Digital Twin Patterns

Metamodel

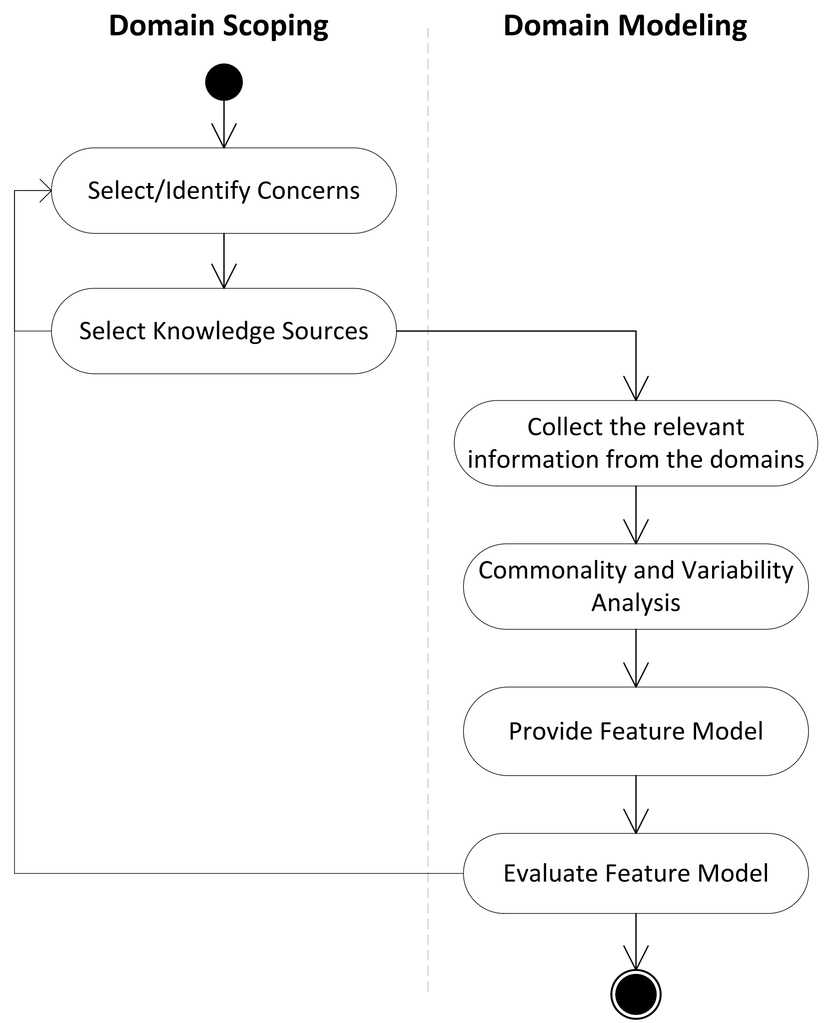

Systems Engineering
builds
System
adopts
is-a
Lifecycle Process
Digital Twin
Based System
has
Architecture
includes
has
designed
using
*
Digital Twin
sync
Physical Object
Architecture Pattern
is-a
*
used in
Lifecycle Stage
System Architecture
Digital Twin Pattern

Adopted Research Method

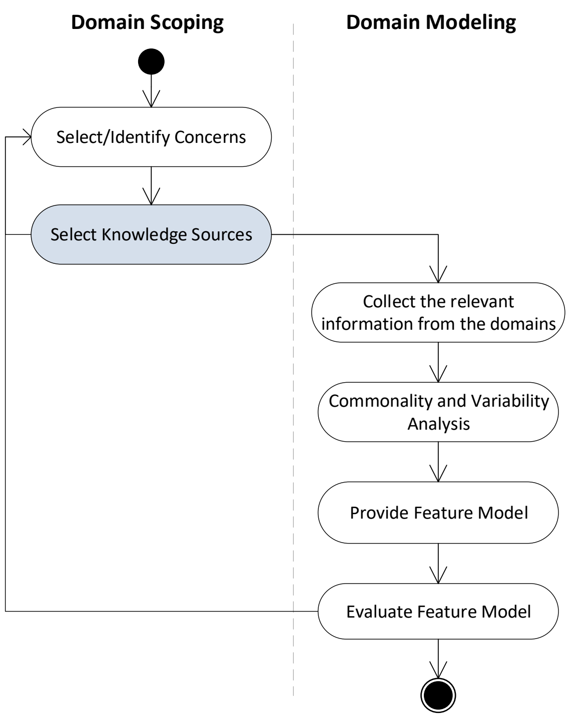


Domain Analysis Process

- **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



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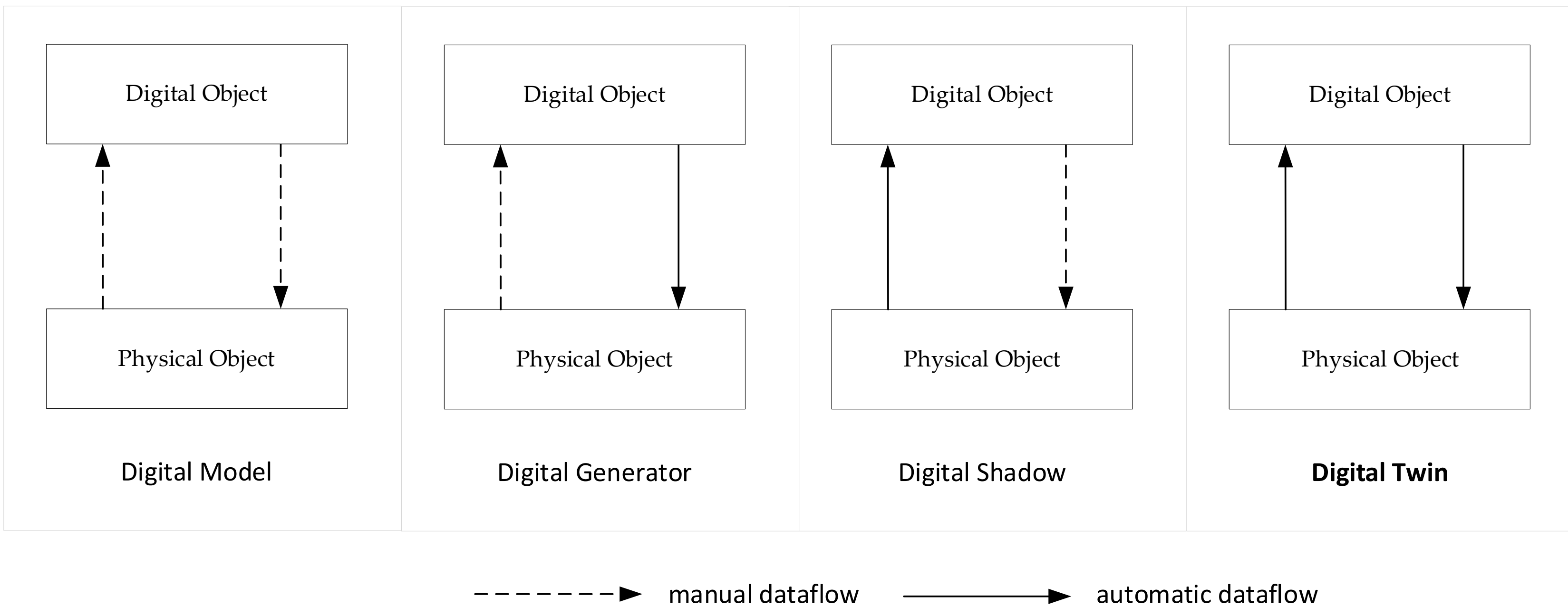
Relationships between digital object and physical object

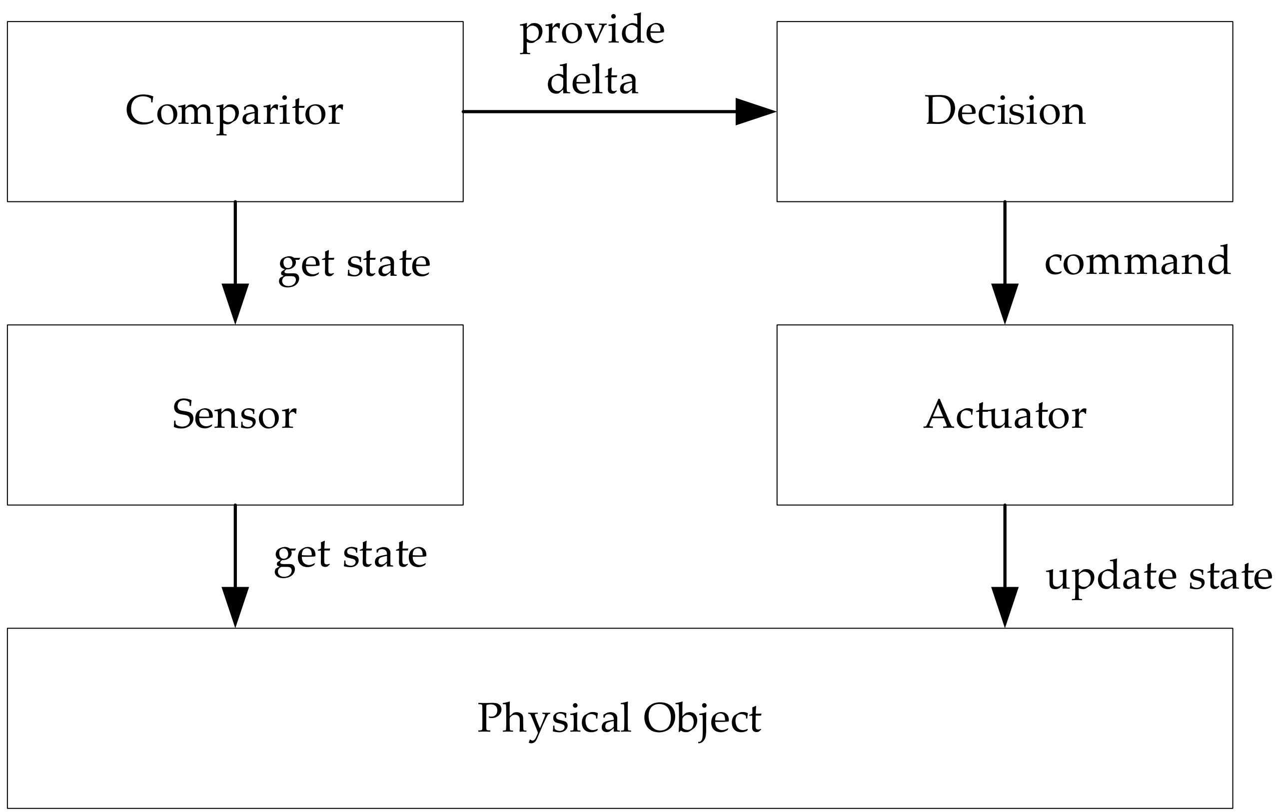


Terms

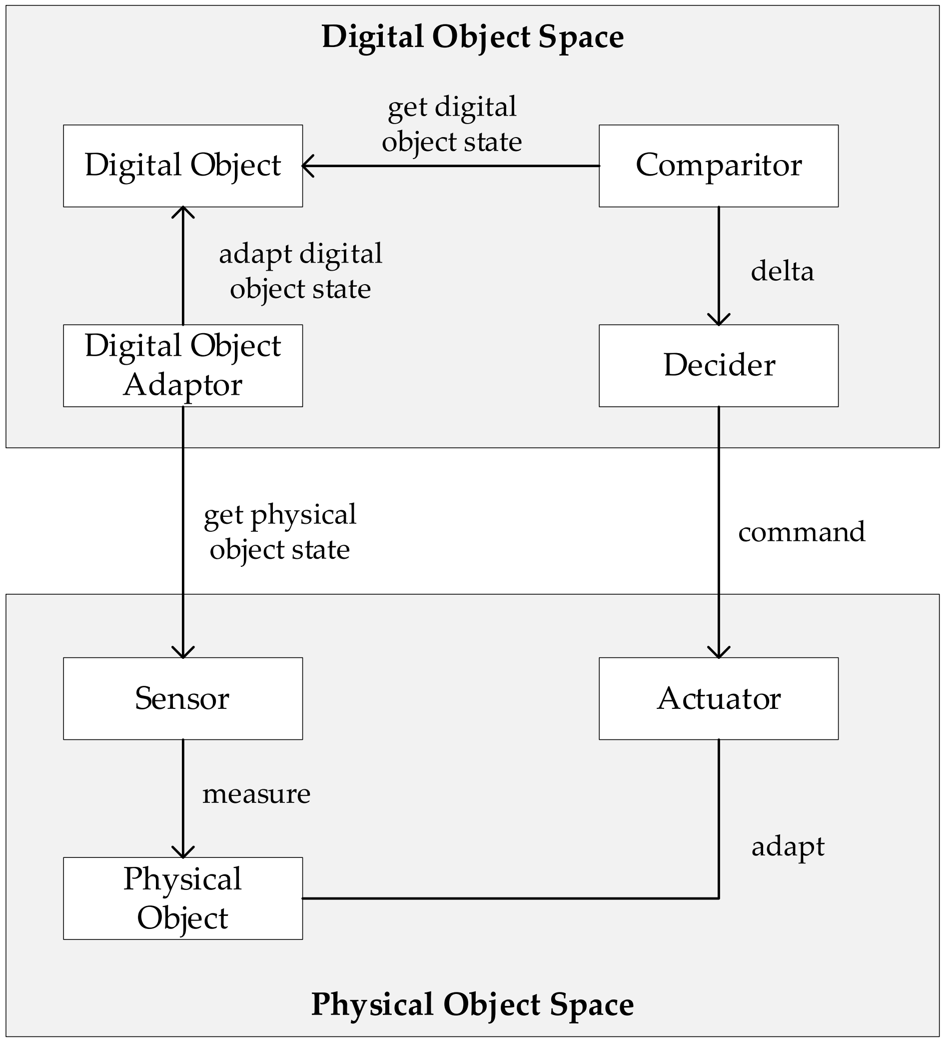
Term	Description
Physical Object	A "real-world" artefact, e.g., a vehicle, component, product, system, model.
Virtual Object	A computer generated representation of the physical object.
Physical Environment	The measurable "real-world" environment within which the physical object exists.
Virtual Environment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

Jones, D.; Snider, C.; Nassehi, A.; Yon, J.; Hicks, B. Characterising the Digital Twin: A systematic literature review.
CIRP J. Manuf. Sci. Technol. 2020, 29, 36–52, doi:10.1016/j.cirpj.2020.02.002., 2020.

Conceptual Model – Control System



Conceptual model for Control-based digital twin



Digital Twin Pattern Catalog

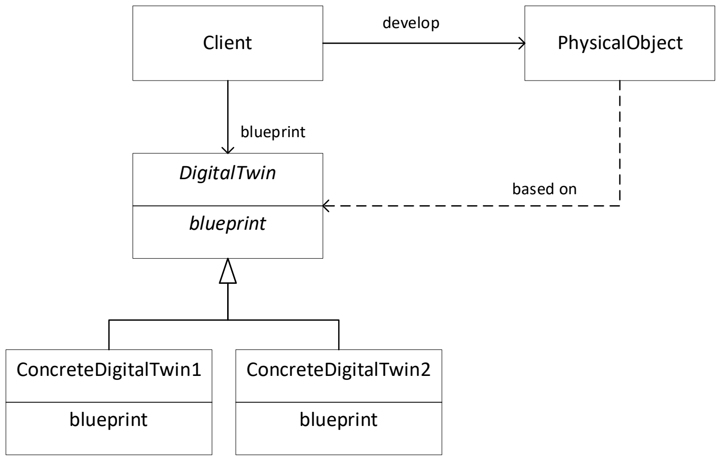
Digital Model Pattern
Digital Generator Pattern
Digital Shadow Pattern
Digital Matching Pattern
Digital Proxy Pattern
Digital Restoration Pattern
Digital Monitor Pattern
Digital Control Pattern
Digital Autonomy Pattern

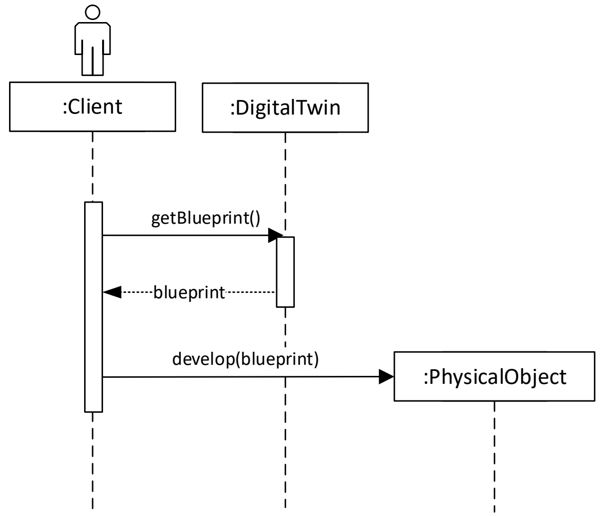
Documentation Template

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

Digital Model Pattern

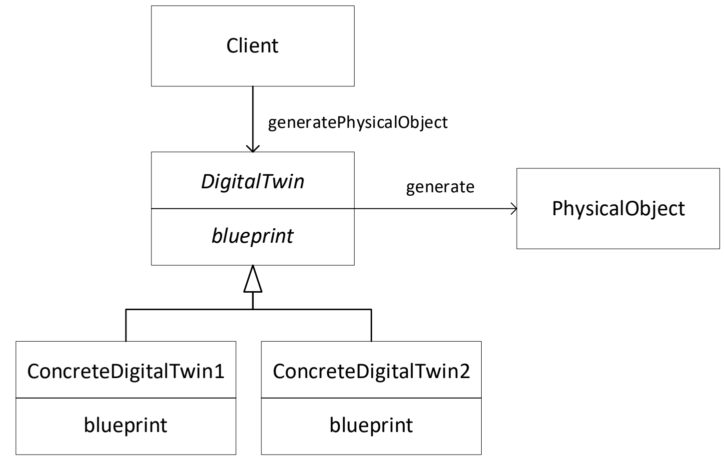
- *Name*—Digital Model.
- *Lifecycle Stage*—Concept, Development, and Production stages.
- *Context*—A physical object needs to be manually developed based on a digital object.
- *Problem*—Based on a digital model a physical object needs to be created.
- *Solution*—The digital twin object is used as 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.

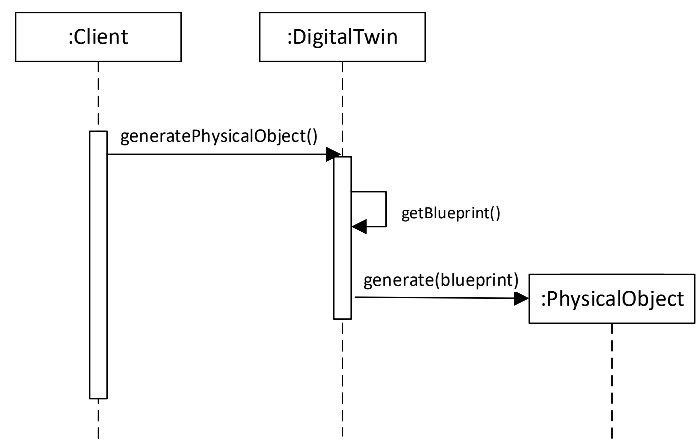




Digital Generator Pattern

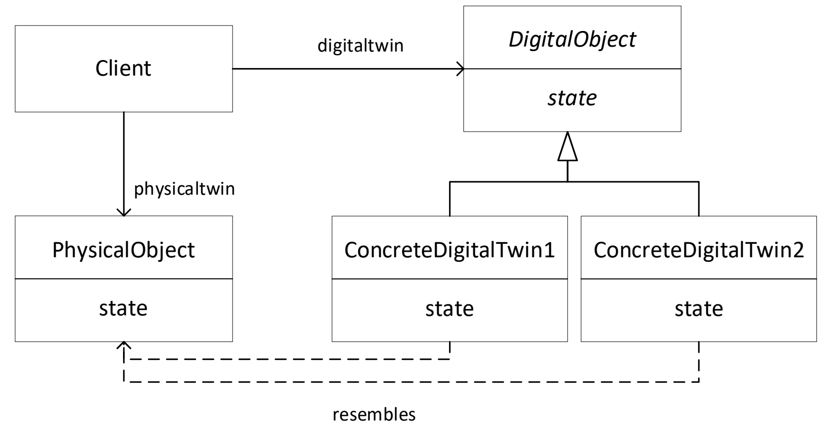
- *Name*—Digital Generator.
- *Lifecycle Stage*—Concept, Development, and Production stages.
- *Context*—A physical object needs to be automatically developed based on a digital object.
- *Problem*—Based on a digital model a physical object needs to be automatically created.
- *Solution*—The digital 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

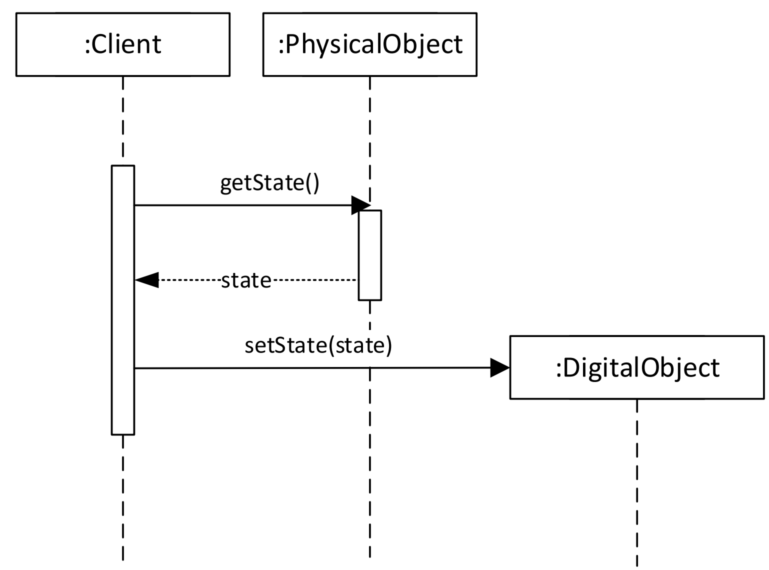




Digital Shadow Pattern

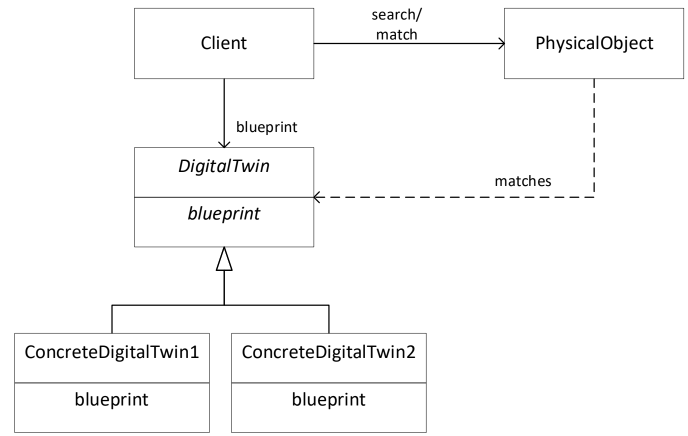
- *Name*—Digital Shadow.
- *Lifecycle Stage*—Concept, Development, and Production stages.
- *Context*—A digital twin needs to be developed for a physical object.
- *Problem*—For a given physical object a digital twin needs to be developed. Various motivations may be given for the need for digital twin 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.

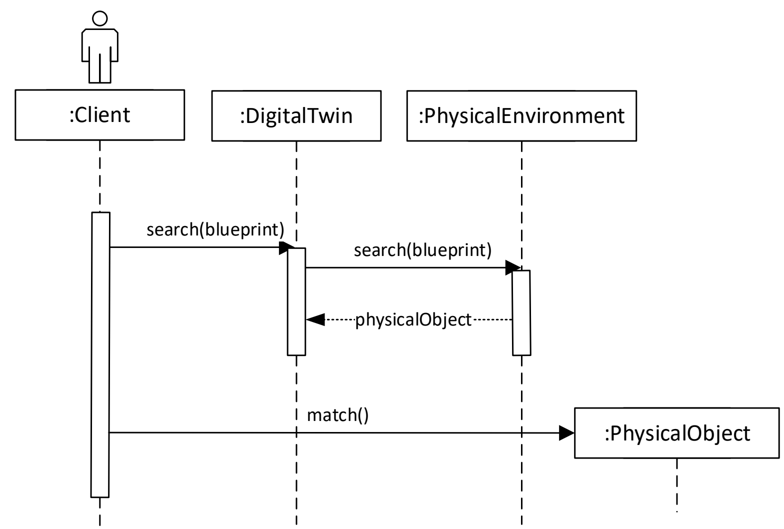




Digital Matching Pattern

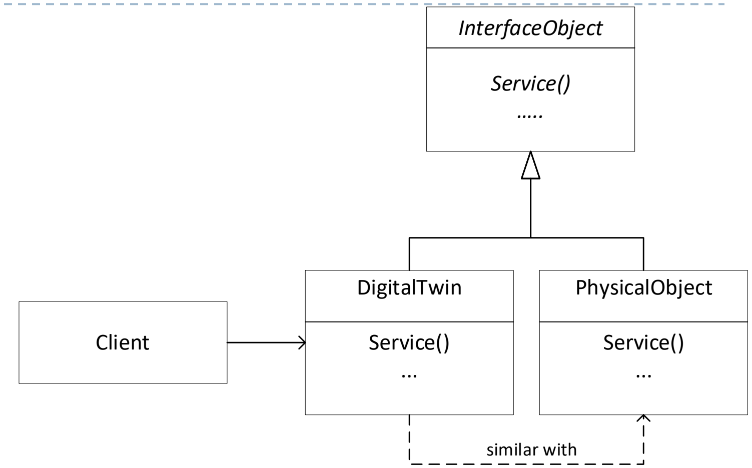
- *Name*—Digital Matching.
- *Lifecycle Stage*—Utilization, Support.
- *Context*—A physical object needs to be found that matches the digital twin.
- *Problem*—Based on a digital model a physical object needs to be found.
- *Solution*—The digital twin object is used by an external client object to find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

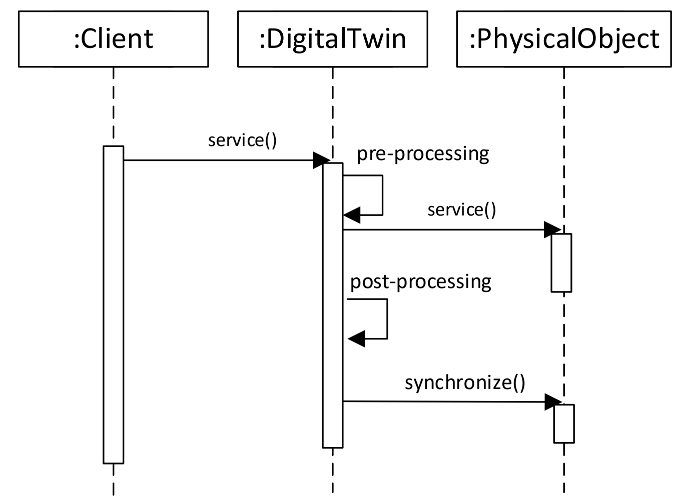




Digital Proxy Pattern

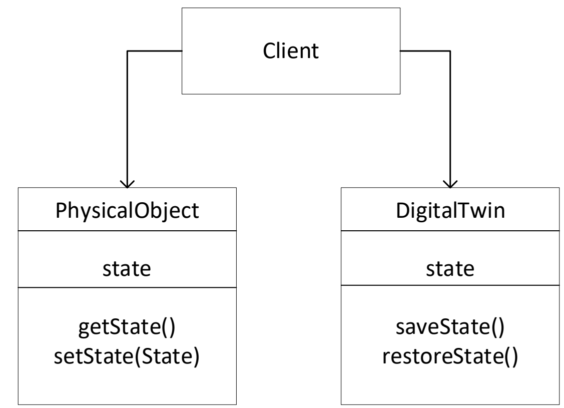
- Name—Digital Proxy
- Lifecycle Stage—Utilization, Support and Retirement stages.
- Context—A digital twin needs to act in case of a physical object.
- Problem—It is often inappropriate to access a physical object directly.
- Solution—The design pattern makes the clients of a component communicate with 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.

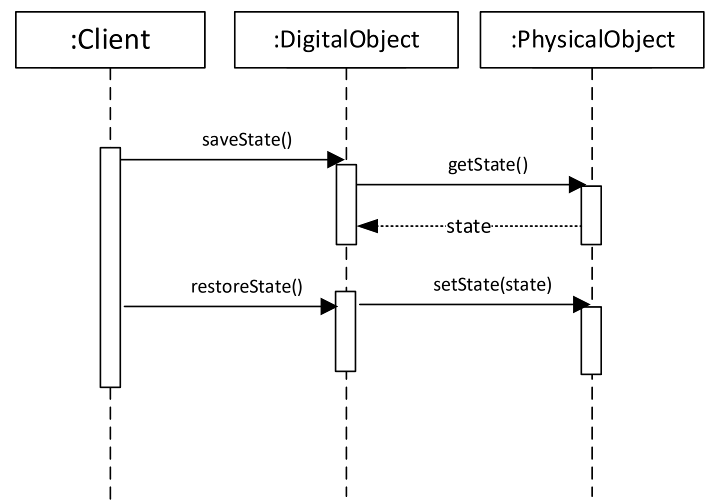




Digital Restoration Pattern

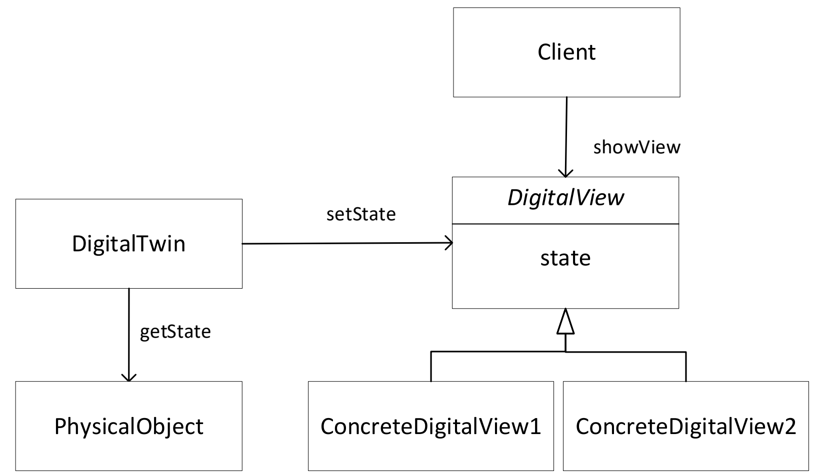
- *Name*—Digital Restoration.
- *Lifecycle Stage*—Utilization and Support stages.
- *Context*—A physical object needs to be restored to its earlier state.
- *Problem*—How can a physical object's state be captured and externalized so that the object can be restored to this state later.
- *Solution*—A 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

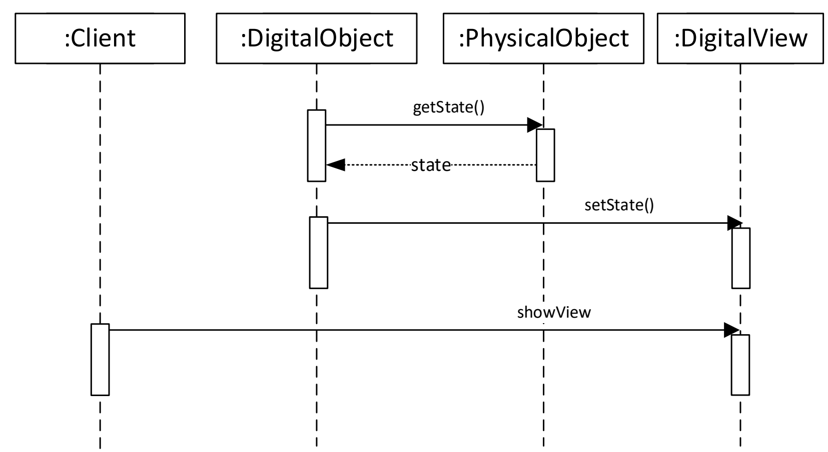




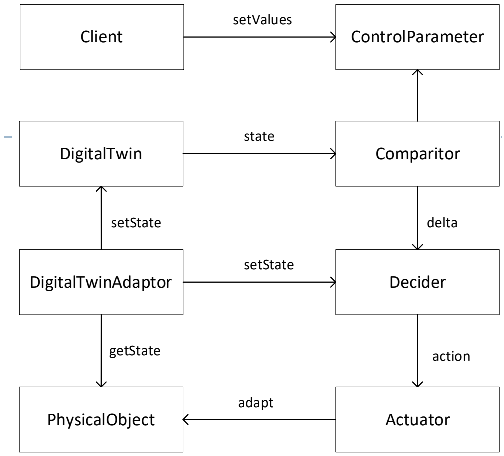
Digital Monitor Pattern

- *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.

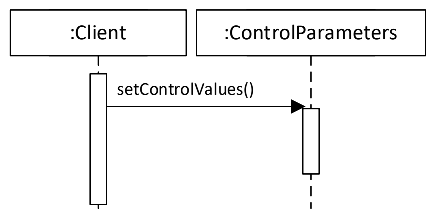


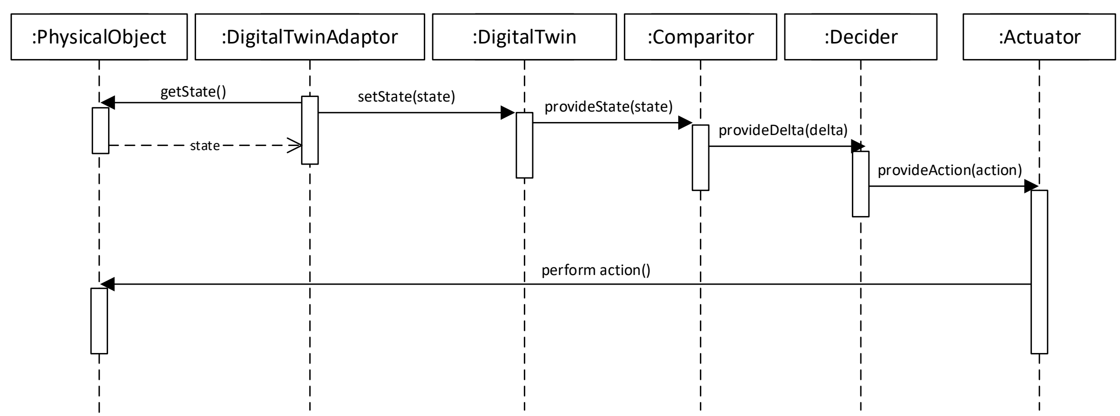


Digital Control Pattern

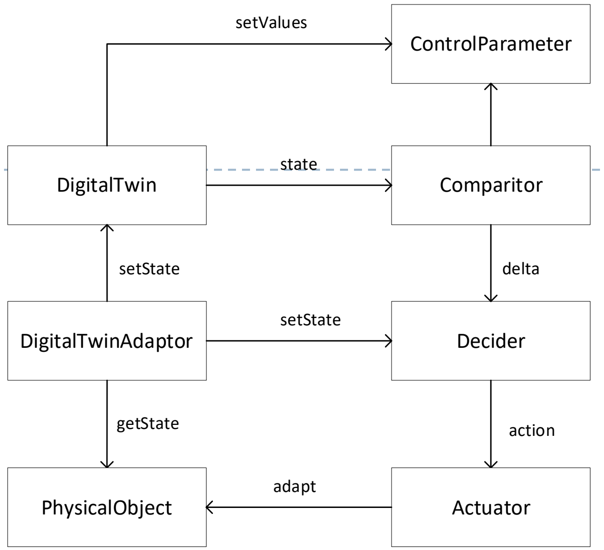


- *Name*—Digital Control.
- *Lifecycle Stage*—Utilization and Support stages.
- *Context*—A physical object needs to be controlled.
- *Problem*—How can a physical object's state be perceived and changed.
- *Solution*—A digital twin is connected to the physical object. The digital twin monitors the physical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

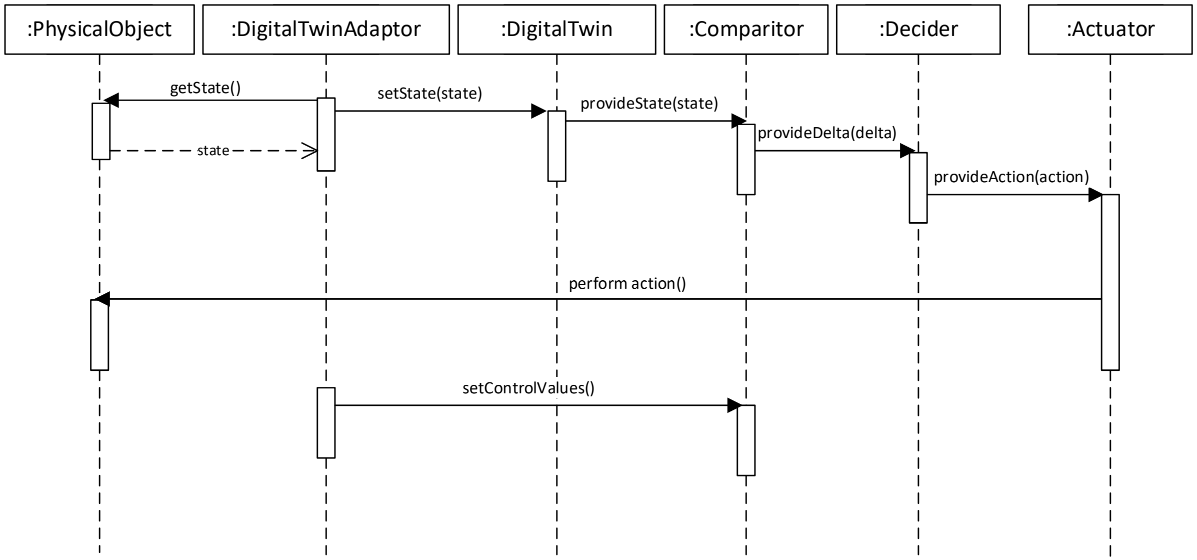




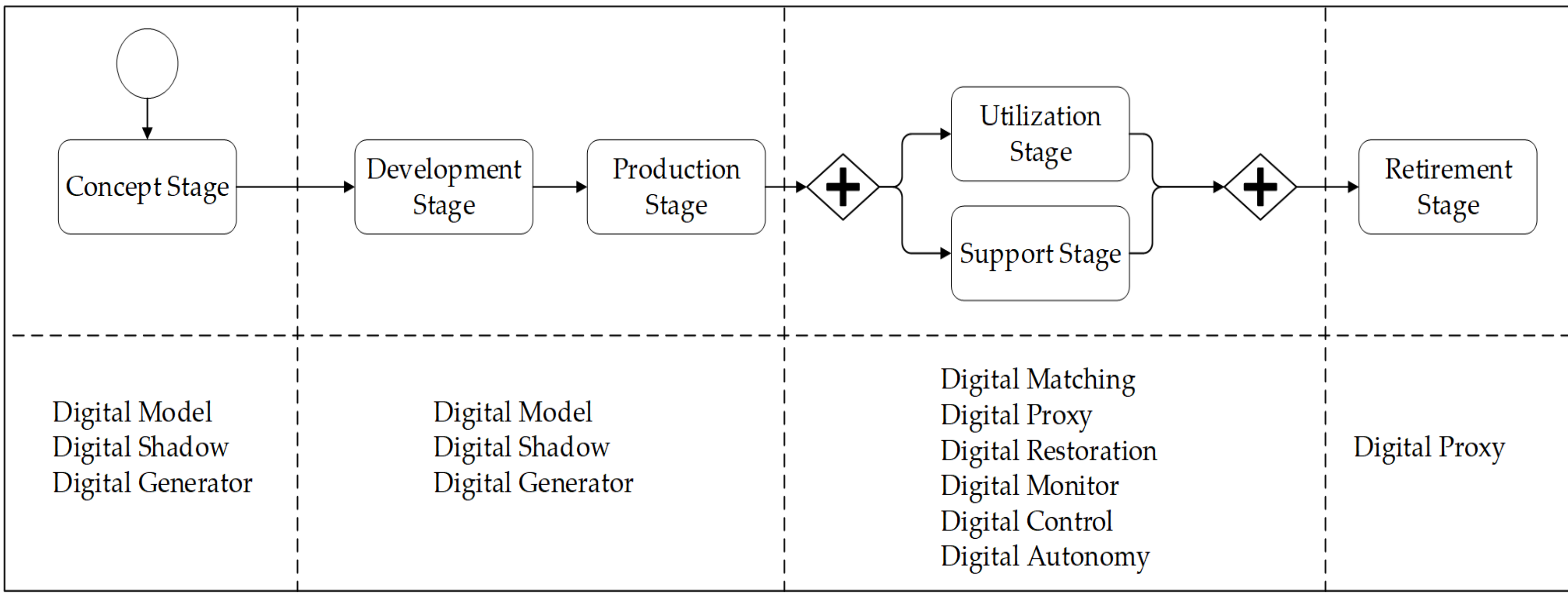
Digital Autonomy Pattern



- *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



Case Study

Case Study Design

Case Study Design Activity	Case Study
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

Trial/Sector	Use Case	Description
Arable	**Within-field management zoning**	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.
Dairy	**Happy Cow**	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.
Vegs	**Chain-integrated greenhouse production**	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.

Use Case Digital Twin Pattern	Within Field Management Zoning	Happy Cow	Chain-Integrated Greenhouse Production
Digital Model	-	-	Each greenhouse production system can be developed based on a digital model (design)
Digital Generator	-	-	Digital twin could be used to (automatically) generate greenhouse production systems.
Digital Shadow	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)	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)	Initially, a digital model of a greenhouse production system 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)
Digital Matching	The pattern can be used to support the analysis and classification of the fields based on defined properties in the digital twin	Properties as defined in the digital twin (e.g., for disease detection) can be used to match with cows.	The pattern can be used to support the analysis and classification of the products in a greenhouse, based on defined properties in the digital twin
Digital Proxy	A digital twin can be used as a proxy to provide information about the fields.	A digital twin can be used as a proxy to provide information about a cow.	A digital twin cane be used as a proxy to provide information about greenhouse production.
Digital Restoration	-	-	Digital model includes undo/redo facilities to restore/update the state of greenhouse production
Digital Monitor	Fields can be monitored by digital twin.	Cows can be monitored by digital twin for various physiological data (temperature, rumen and body activity, pH level).	Greenhouse production systems can be monitored by digital twins.
Digital Control	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).	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.	Based on a sophisticated data analytics decision support, yields are predicted and task instructions prepared for greenhouse equipment (e.g., climate, lighting, and irrigation).
Digital Autonomy	-	-	-

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