Software Engineering Curriculum

Leveraging Blockchain-Enabled Digital Twins in Healthcare

Supervisor: **Mubashar Iqbal, PhD**

Xinjian Zhang

4 June 2025

Motivation

Growing **Challenges** in **Modern Healthcare**

- Rising Costs
- Fragmented Data
- High Demand for Personalized Care
- Data Security Concerns

...

Emerging technologies offer new possibilities

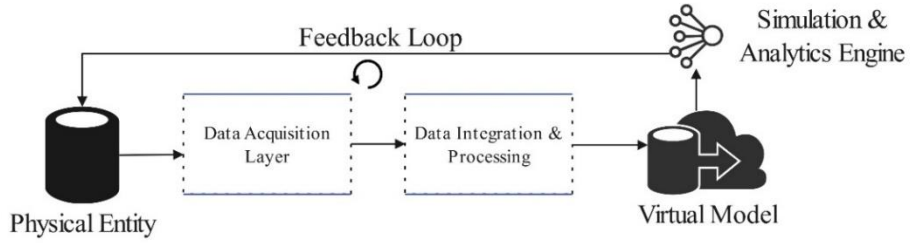
Digital Twins + Blockchain

Toward secure, intelligent, and personalized care

Baseline & Problem Context

Digital Twin (DT)

- Real-time virtual replicas of physical entities
- Enable real-time monitoring, simulation, and prediction



Ensures
Data Trust & Security

Blockchain

- Decentralized, tamper-proof, and auditable ledger

Physical Healthcare System

GOAL

Design and implement a blockchain-enabled **Healthcare Digital Twin (HDT)** Framework

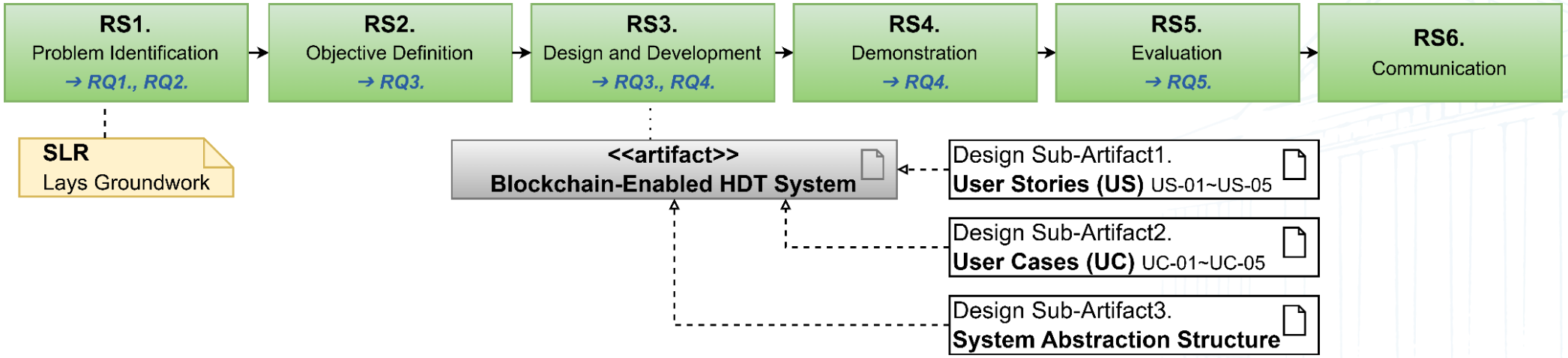
To support secure and intelligent healthcare delivery

Research Questions & Research Method

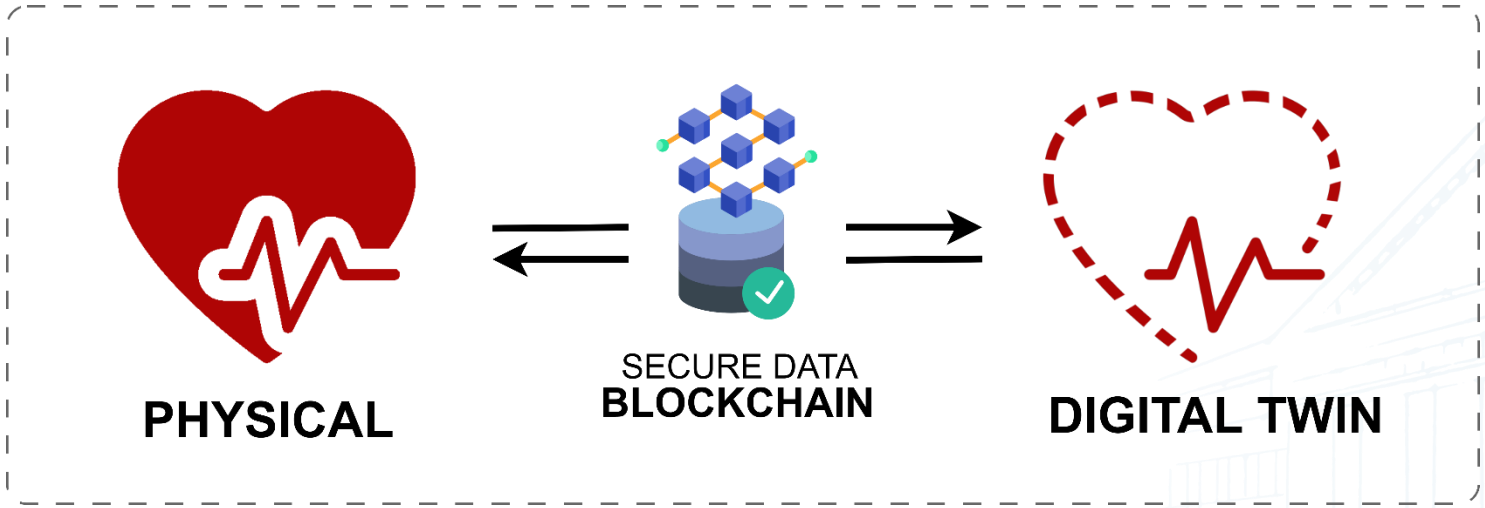
Main RQ: How can blockchain-enabled Digital Twins enhance healthcare systems?

RQ1.	RQ2.	RQ3.	RQ4.	RQ5.
DT Compoment	Blockchain Integration	Design	Implementation	Evaluation

Research Method: Design Science Research (DSR)



Contribution: Blockchain and Digital Twin-based Healthcare System



Systematic Literature Review (SLR)

Answer to RQ1., RQ2.

(DT Components, Blockchain Integration)

Search

Search String: ("Digital Twin" AND "Healthcare" AND "Blockchain")

Screen

Inclusion Criteria (IC), Exclusion Criteria (EC)

3,884 → 1,706→ **18 Papers**

Extract

Extracted Items Focus: DT Components, Blockchain Integration

Analyze

Literature Review Questions (LRQs):

- **LRQ1:** Identify healthcare **use cases** of DTs
- **LRQ2:** Define **key components** of DTs in healthcare
- **LRQ3:** Explore **challenges and limitations** of HDT
- **LRQ4:** Examine **blockchain integration** with DTs in healthcare

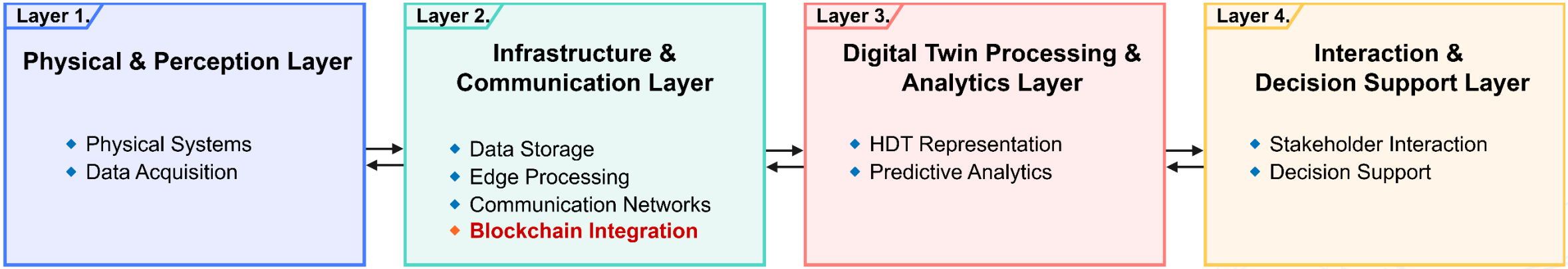
SLR Findings

- Inspired system design
- Identified 6 key components

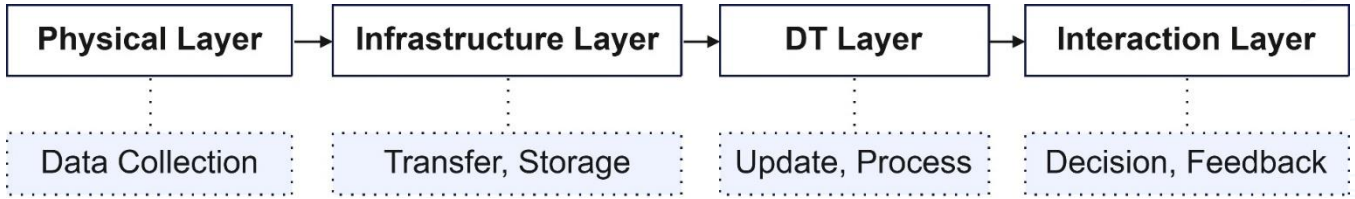
Proposed Healthcare Digital Twin Framework Architecture

Answer to RQ3.
(Design)

4-Layer Architecture



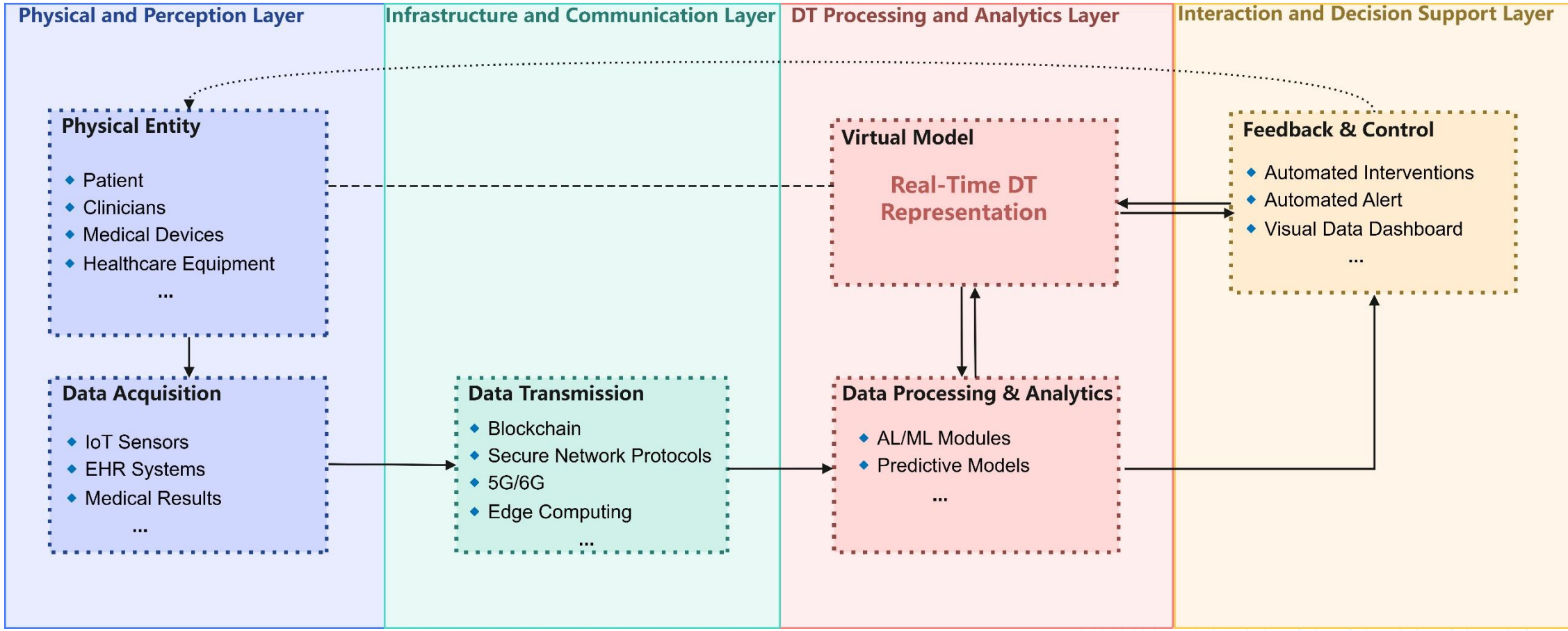
Workflow



Components of the HDT Framework

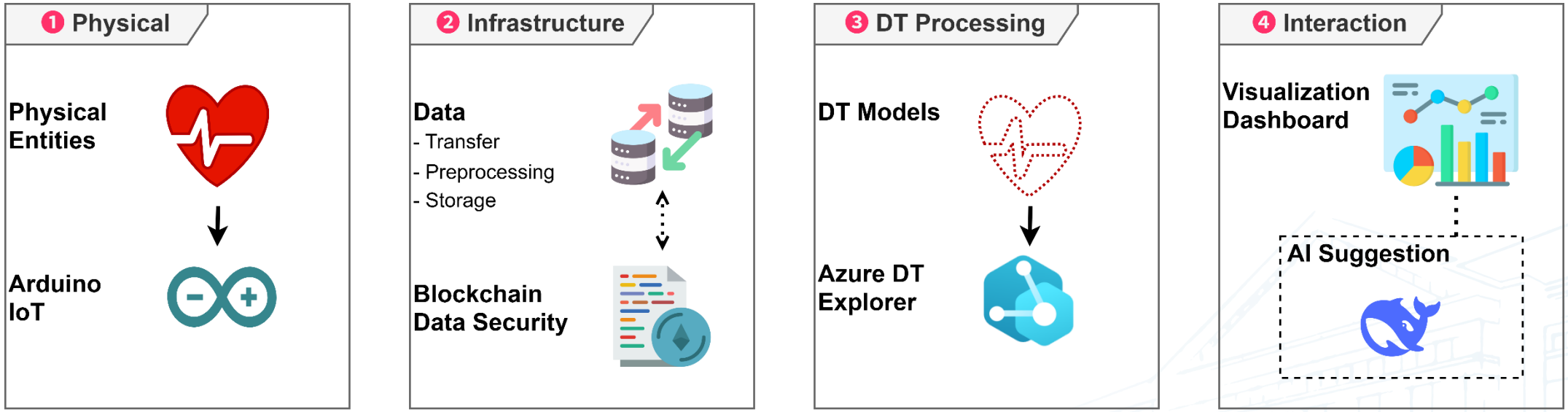
Answer to RQ3.
(Design)

*6 Core Components from **SLR Findings***



Proof of Concept

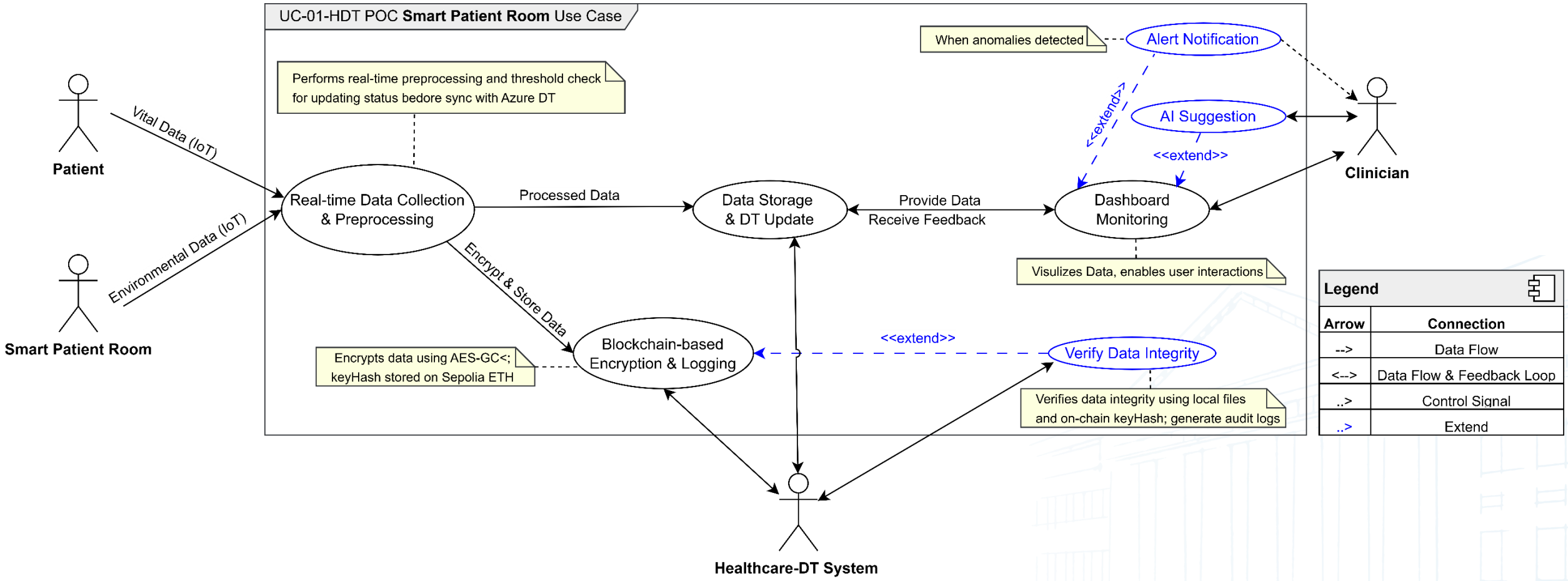
Answer to RQ4.
(Implementation)



Prototype Implementation Overview

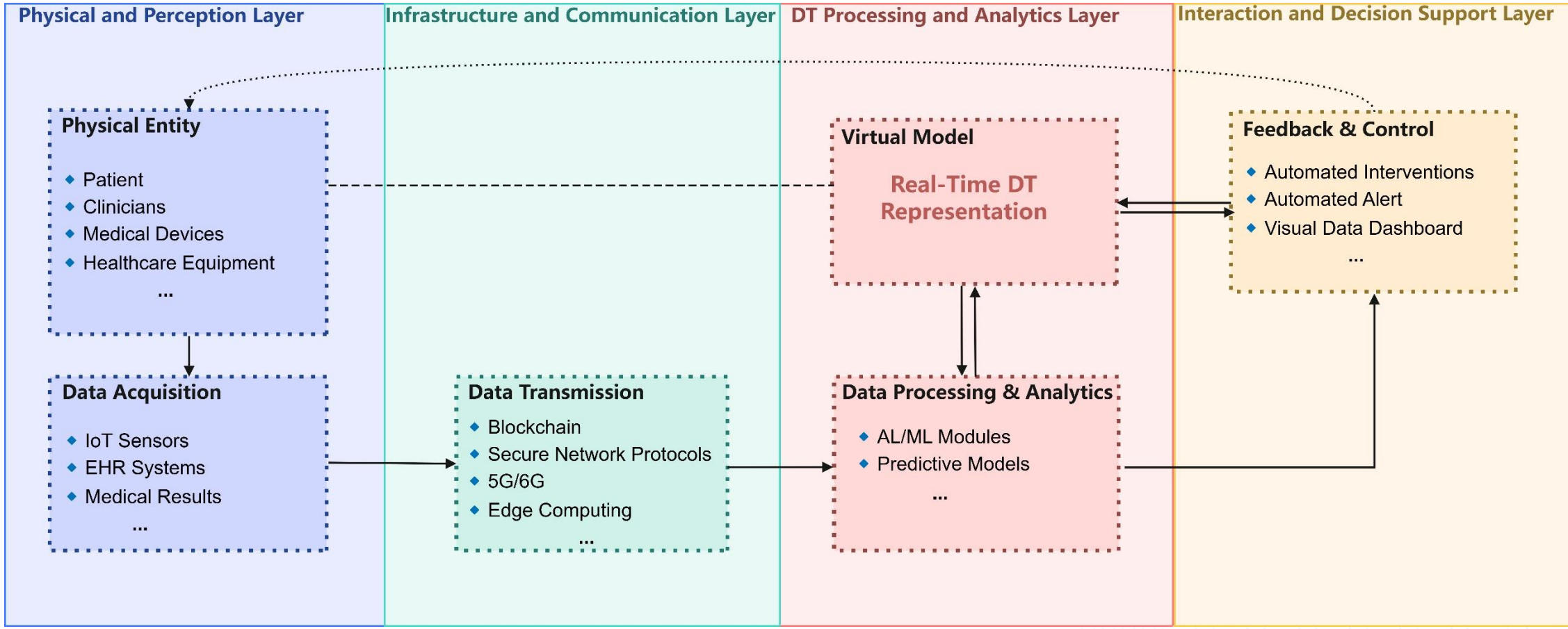
Smart Patient Room - Use Case

Design Sub-Artifact2.
User Cases (UC) UC-01~UC-05 → UC-01-HDT-POC **Smart Patient Room**



Why? ◆Reflects realistic healthcare settings ◆Technically feasible ◆Covers: monitoring, anomaly alerts, secure data storage

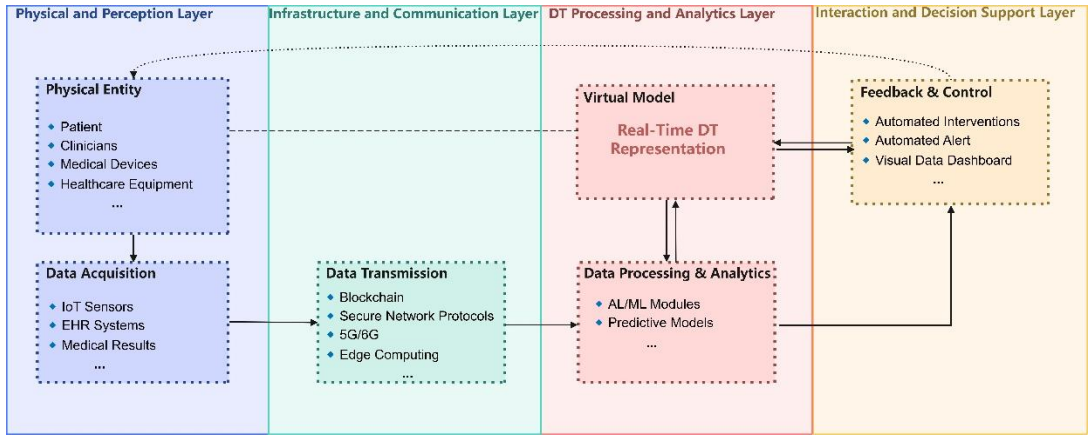
HDT Framework



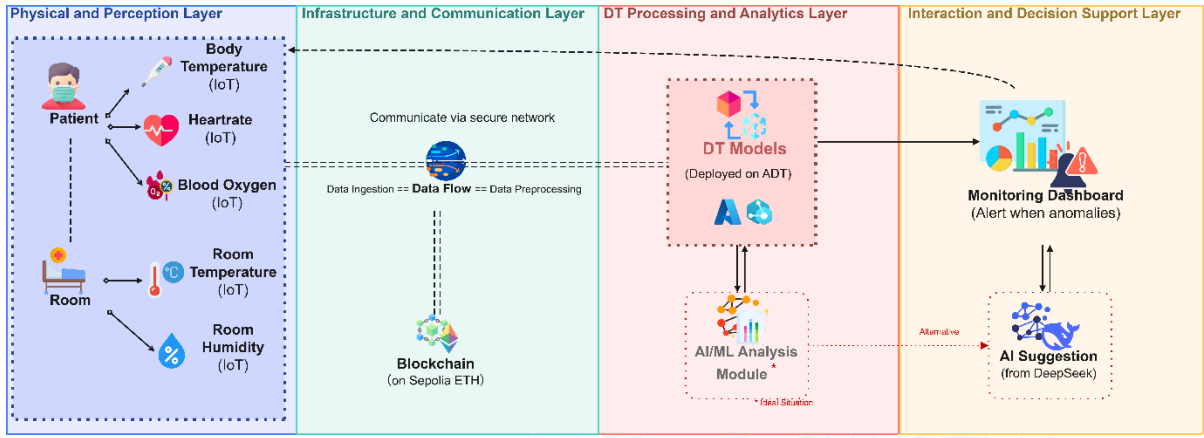
HDT Framework

Instantiation of HDT Framework

UC-01-HDT-POC

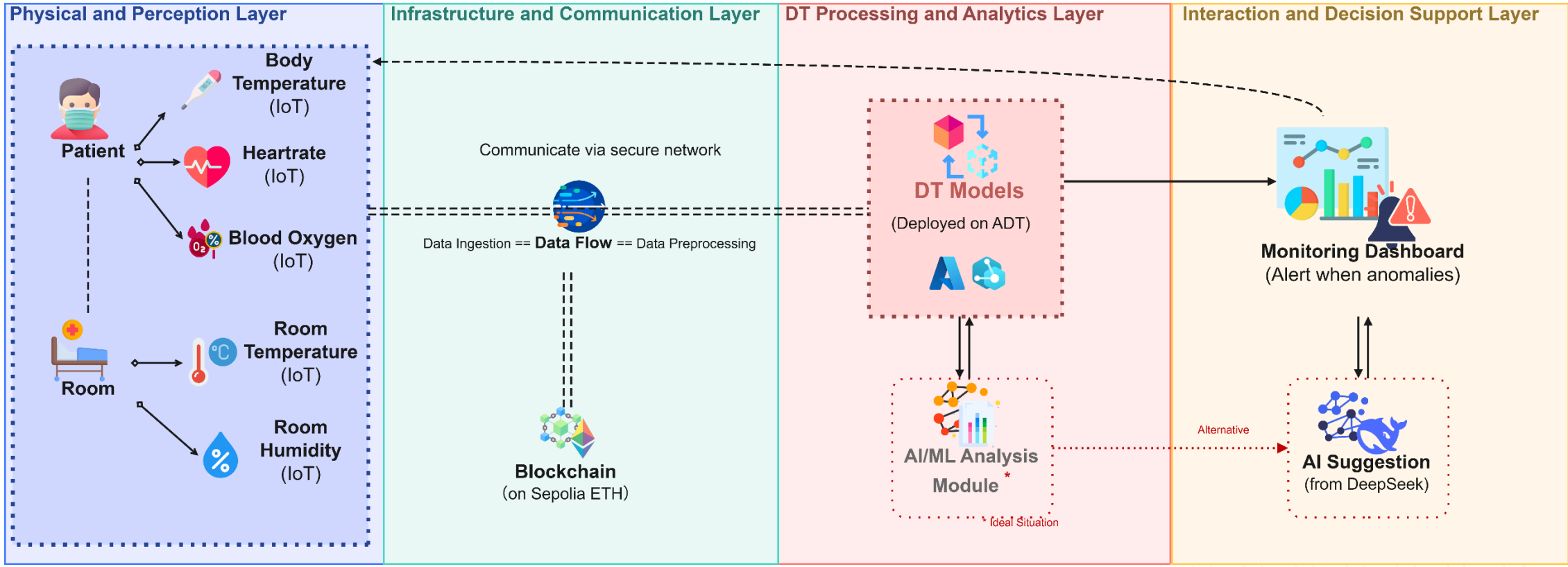


HDT Framework

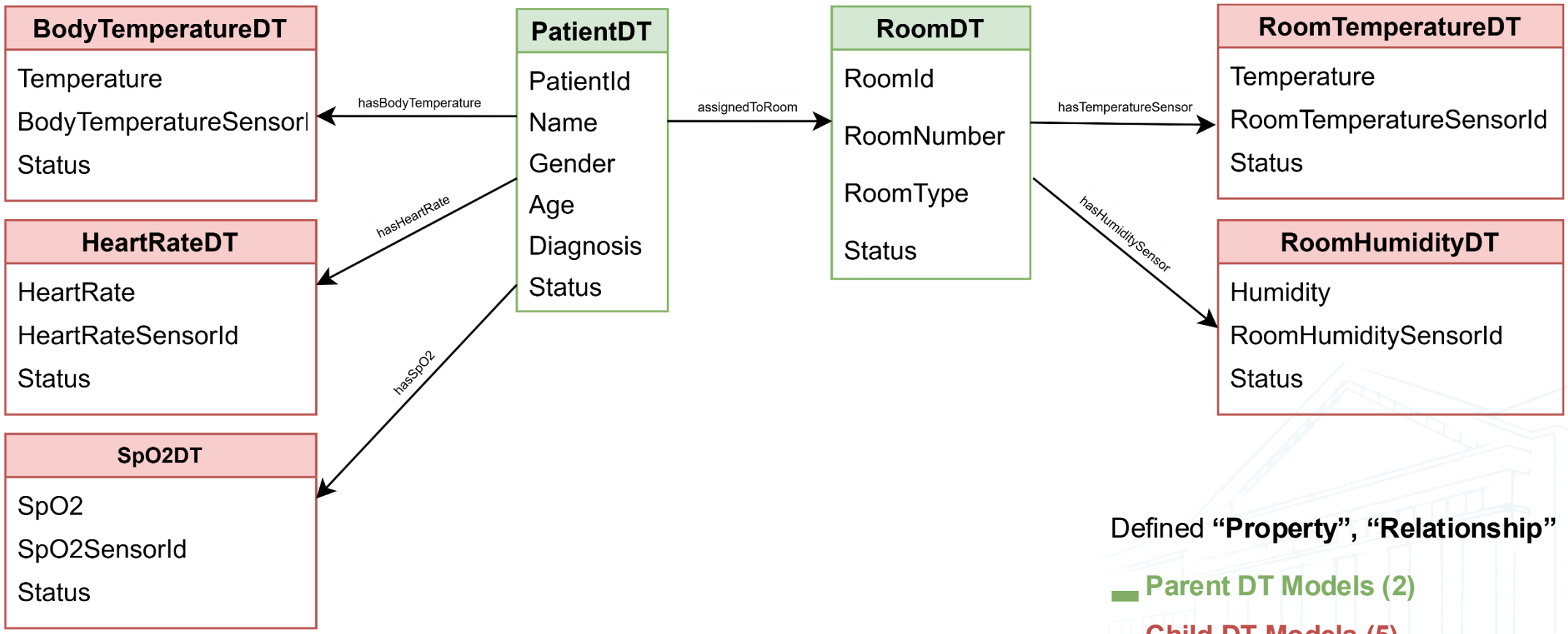


Smart Patient Room HDT Framework

Smart Patient Room - HDT Framework



Digital Twin Models



Defined **“Property”, “Relationship”**

- Parent DT Models (2)
- Child DT Models (5)

DT Models on Azure Digital Twin (ADT) Explorer

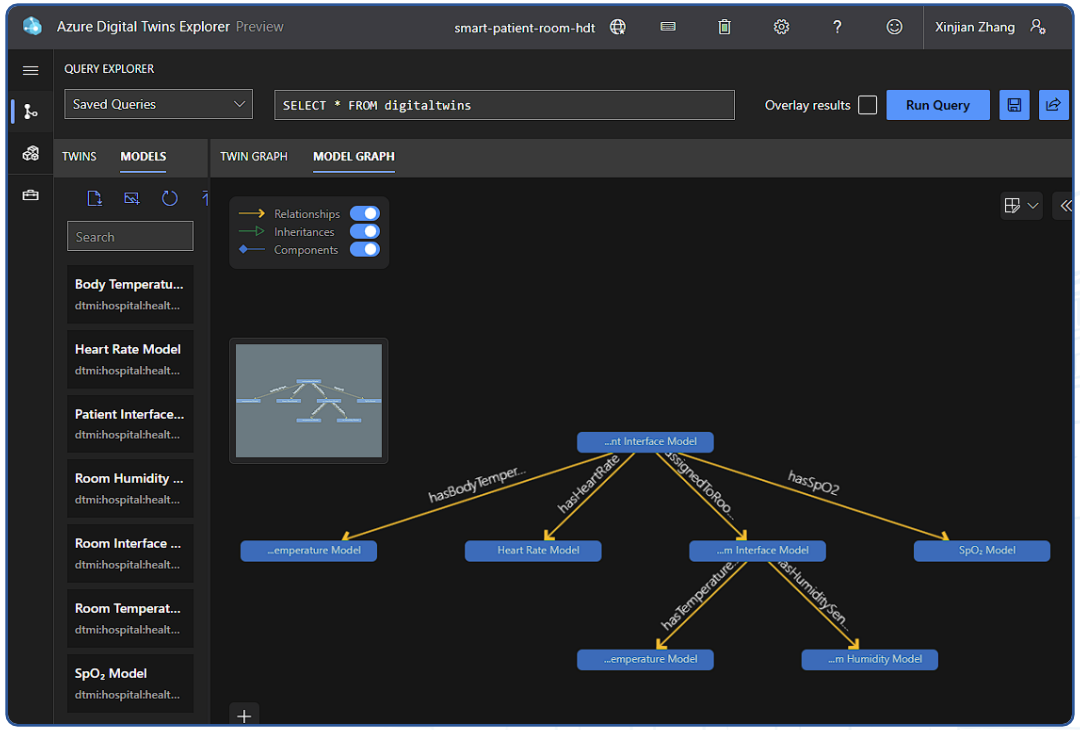
```
{
    "@id": "dtmi:hospital:healthcare:room:humidity;1",
    "@context": "dtmi:dtdl:context;2",
    "@type": "Interface",
    "displayName": "Room Humidity Model",
    "contents": [
        {
            "@type": "Property",
            "name": "Humidity",
            "schema": "double",
            "description": "Humidity level of the room",
            "writable": true
        },
        {
            "@type": "Property",
            "name": "RoomHumiditySensorId",
            "schema": "string",
            "description": "Unique ID of the room humidity sensor",
            "writable": false
        },
        {
            "@type": "Property",
            "name": "Status",
            "schema": "strig",
            "description": "Current status of the room humidity sensor",
            "writable": true
        }
    ]
}
```

DTDL of Room Humidity Model
(room_humidity_model.json)

DTDL (Digital Twins Definition Language)

"A JSON-LD-based language for DTs' structure and behavior"

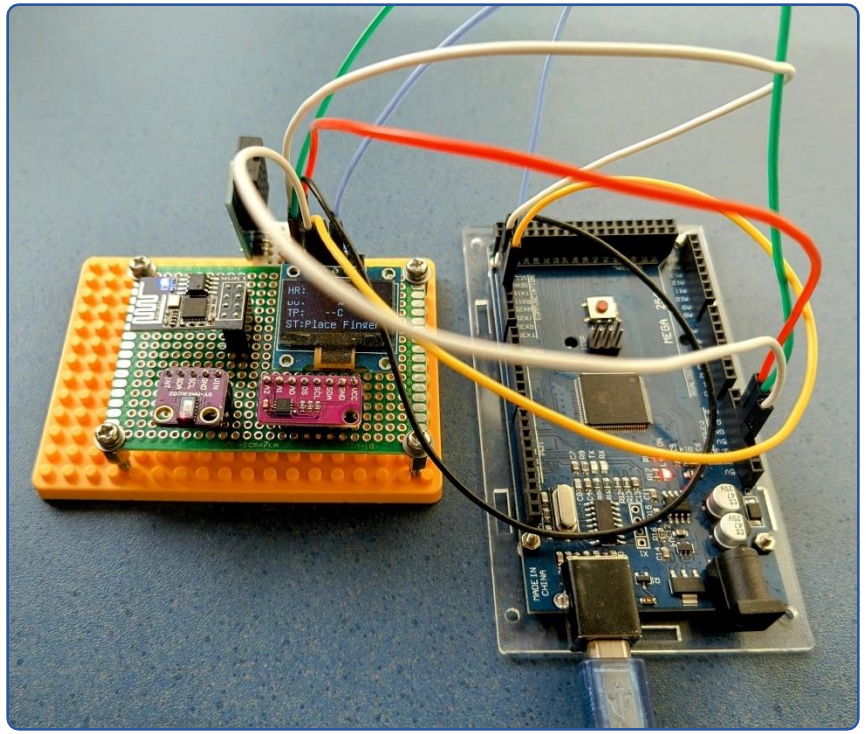
Used to define the **structure** and **behavior** of DTs
in **Azure Digital Twins (ADT)**



Interface of ADT Explorer

IoT-Based Data Acquisition

*"Enables continuous **patient monitoring** and **environmental awareness** for HDT system updates"*



Arduino IoT Settings

Hardware

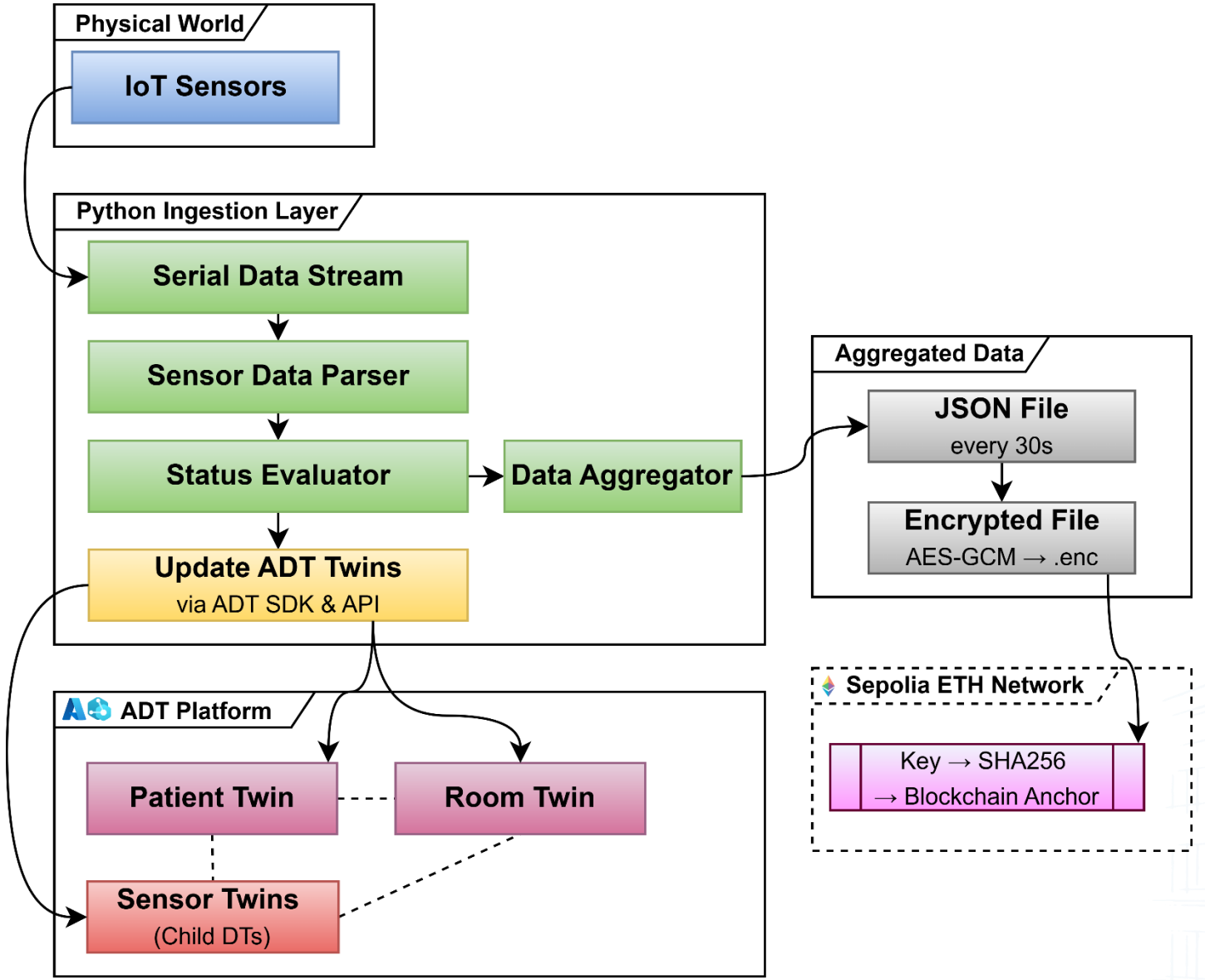
Component	Function
Arduino Mega 2560	Central MCU
MAX30102	Heart Rate and SpO_2 (PPG-based)
MAX30205	Body Temperature
AM2320	Room Temperature & Room Humidity
OLED12864 (SSD1306)	On-device real-time visualization

Data Acquisition: Streamed via Serial in compact format

```
data#<HR>&<SpO2>&<BodyTemp>&<FingerFlag>&<RoomTemp>&<RoomHum>&end#
```

▶ *DEMO*

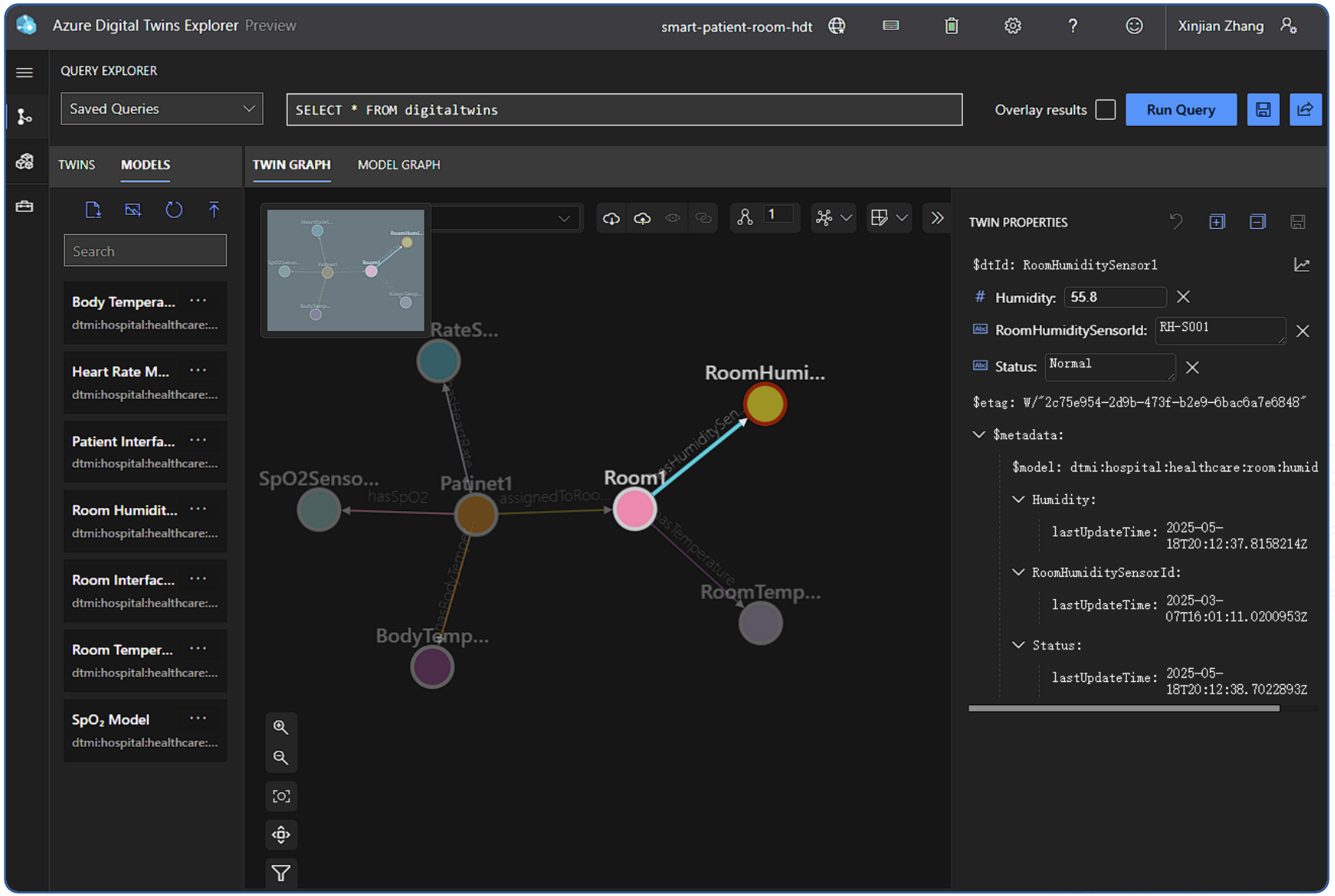
Azure Digital Twins Synchronization



Blockchain Integration in DT

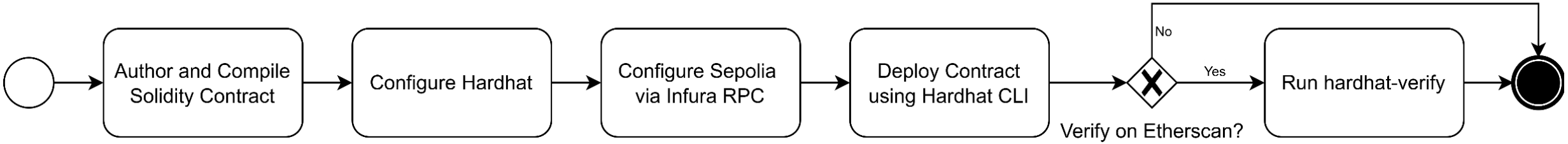
- Secure Data Integrity

Data Synchronization in ADT Explorer

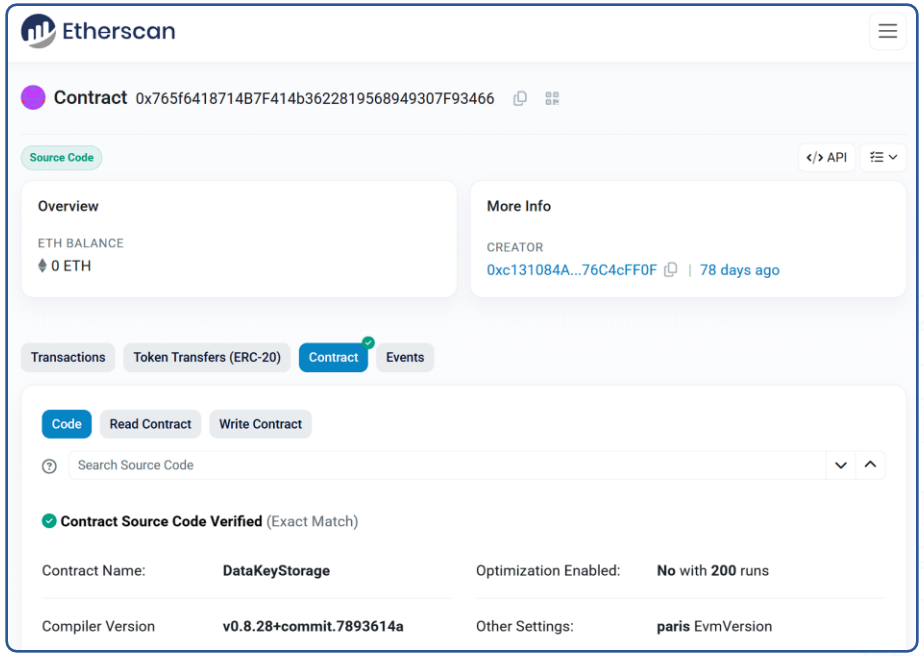


▶DEMO

Blockchain-Based Smart Contract Deployment

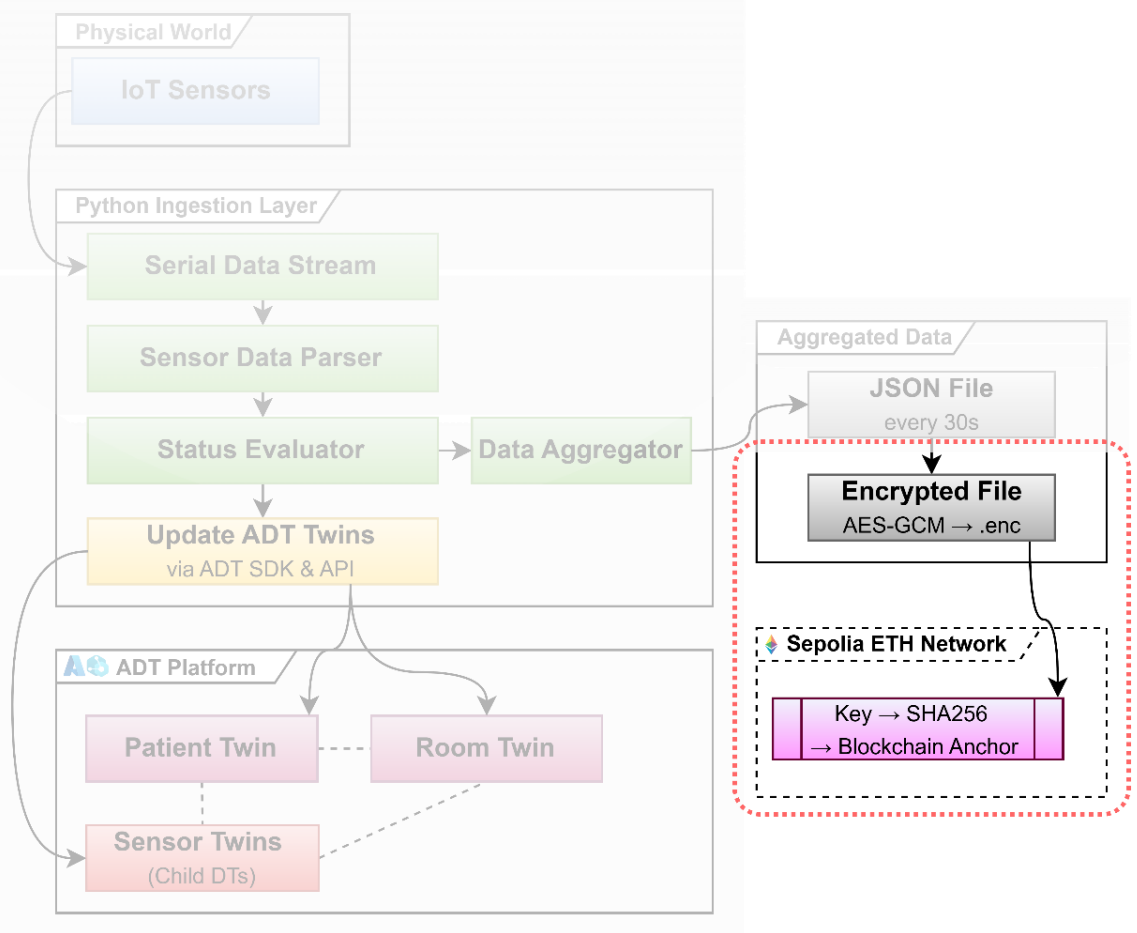


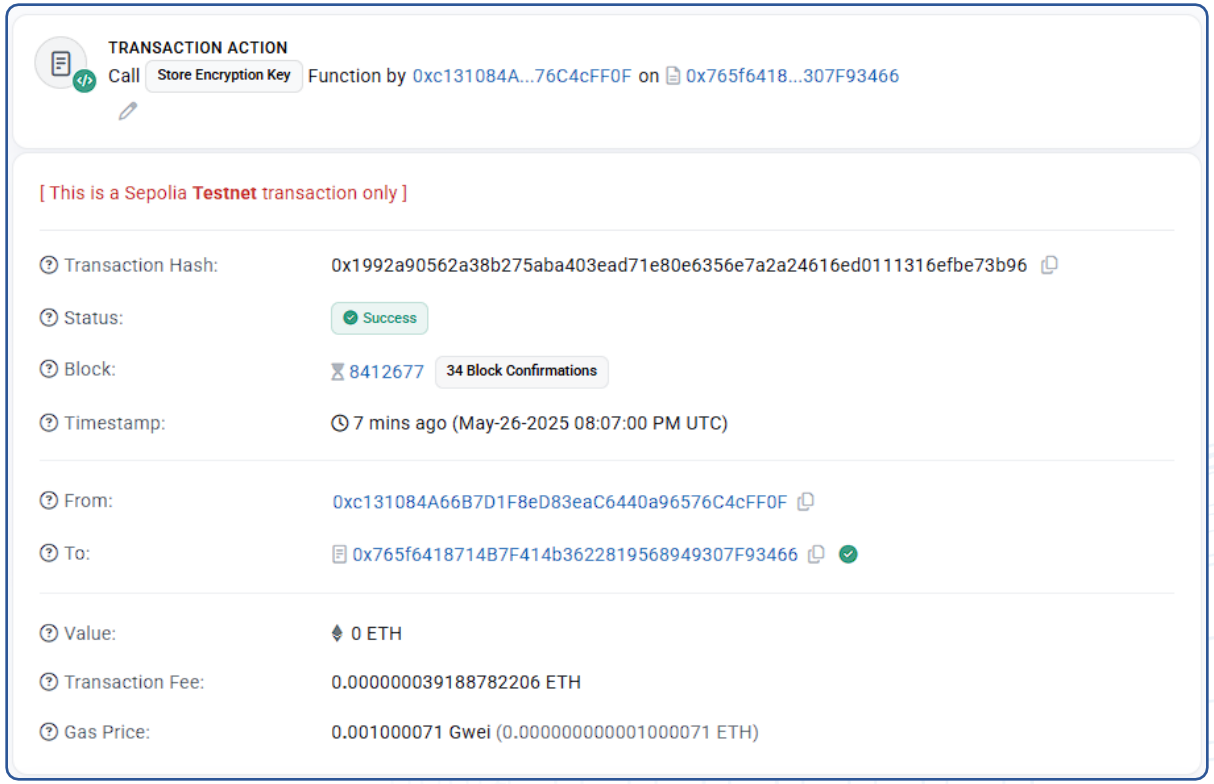
Smart Contract Deployment Process



Verify Contract Deployment on Etherscan

Blockchain Logging on Ethereum

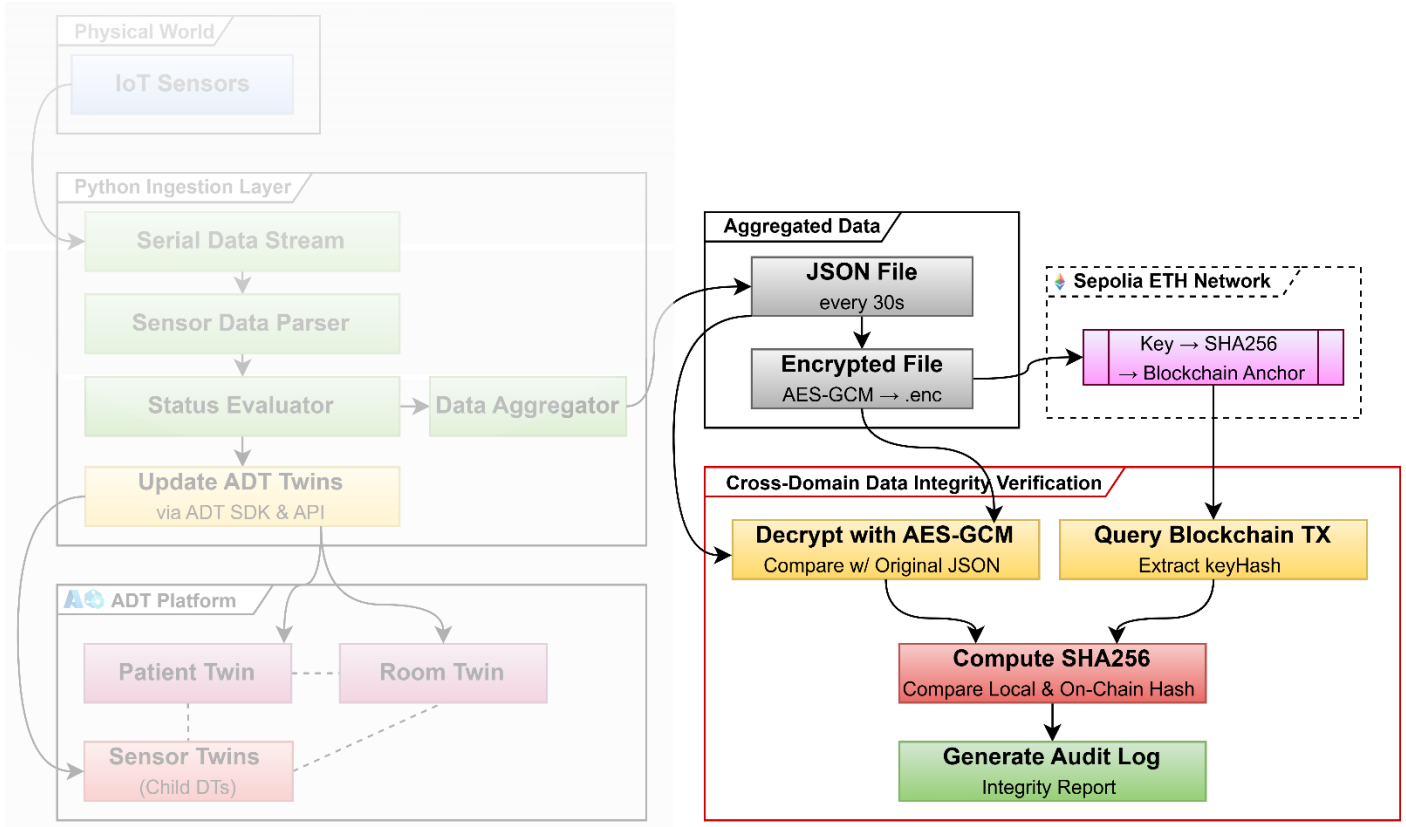


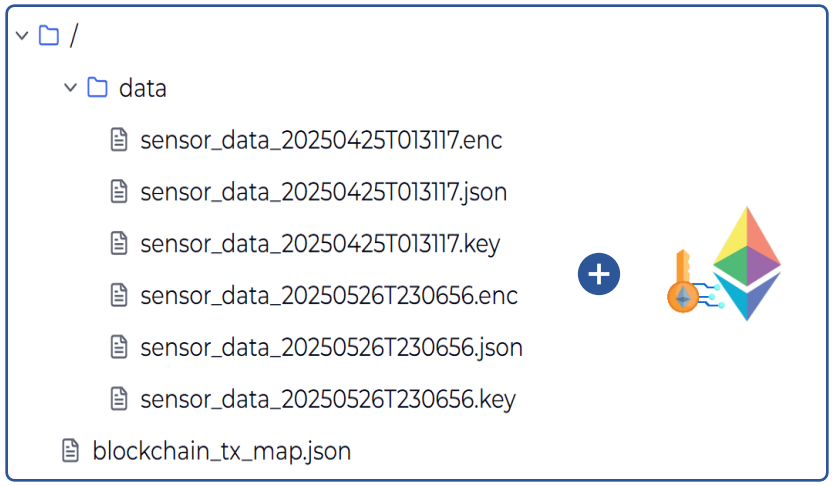


Verify Transaction on Etherscan

▶ *DEMO*

Cross-Domain Data Integrity Verification





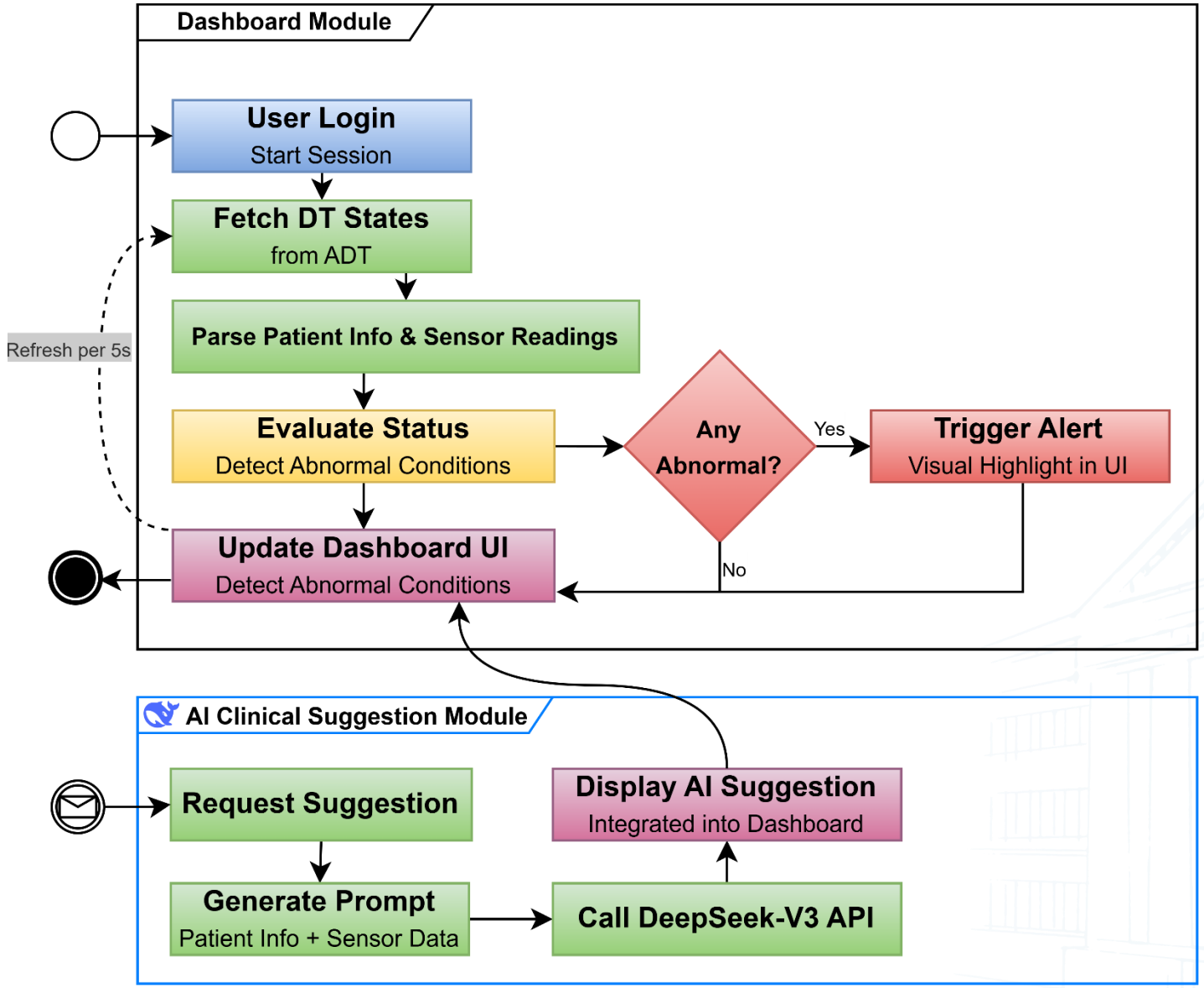
Local files + Encryption Key Stored on Sepolia

```
File 1 - Verifying: sensor_data_20250425T013117
Decryption matched JSON
Blockchain keyHash matched transaction input
Matched transaction hash: 2939a3f68a6e65b683bc5d3b...

File 2 - Verifying: sensor_data_20250526T230656
Decryption matched JSON
Blockchain keyHash matched transaction input
Matched transaction hash: 1992a90562a38b275aba403...

=== Verification Summary ===
Total files verified: 2
Passed: 2
Failed: 0
```

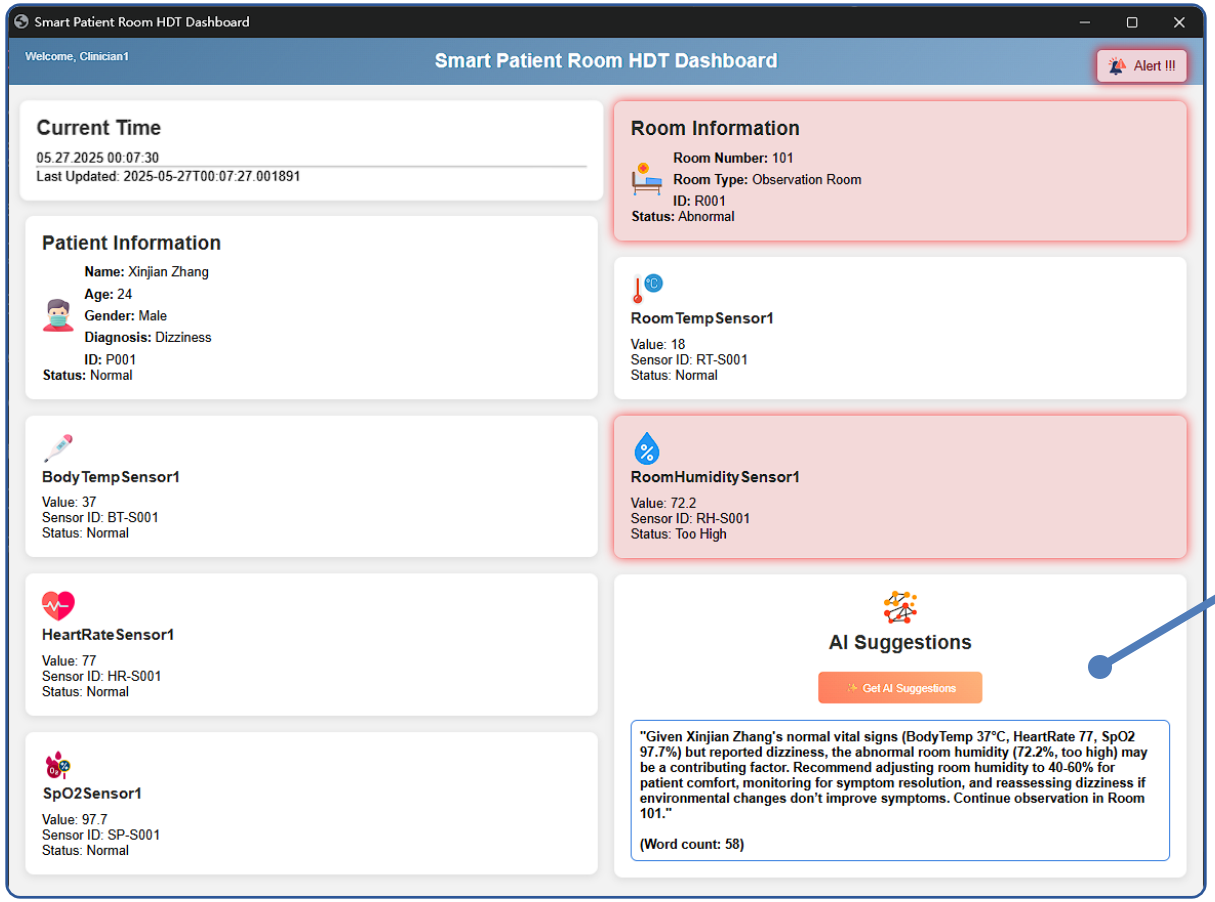
Audit Log in Console

▶ *DEMO*

Real-Time Monitoring Dashboard
With AI-Driven Suggestion



Real-Time Monitoring Dashboard
With AI-Driven Suggestion



Smart Patient Room HDT Dashboard UI

AI Clinical Suggestions

▶DEMO

Evaluation

Semi-structured Qualitative Interview

Answer to RQ5.
(Evaluation)

Evaluation Criteria (5)

Functionality	$q_{1.1}$ *Data accuracy*	$q_{1.2}$ *Blockchain trust*
Services	$q_{2.1}$ *Monitoring usefulness*	$q_{2.2}$ *Feature completeness*
Operations	$q_{3.1}$ *Technical stability*	$q_{3.2}$ *Workflow integration*
Usability	$q_{4.1}$ *Interface intuitiveness*	$q_{4.2}$ *Ease of completing key tasks*
Applicability	$q_{5.1}$ *Suitability for real-world use*	$q_{5.2}$ *Implementation challenges*

Stakeholder Interviews (4 Participants)

Medical Student
Medical Perspective

+ Easy clinical observation
- Lack of decision support
- Not yet meet clinical standards

CS Student
Technical Perspective

+ Clear system logic
+ Good functionality & usability
+ Clear technical feasibility
- Concerns on scalability & network reliance

Nurse
Workflow Perspective

+ Simple interface
+ Easy to use
- To enhance warning mechanisms
- To enhance response capabilities

Patient Rep.
User-Concern

+ Reassured by blockchain
- Needs clearer data use explanations

Feedback

- Confirms feasibility
- Reveal improvement

Insights & Conclusion

Limitations

- Low accuracy sensors, Limited evaluation (small sample, qualitative only)

Future Work

- Build a more comprehensive AI models, Expand quantitative evaluation

---

Conclusion

- Modular Healthcare Digital Twin (HDT) framework: real-time monitoring, data security, decision support
- Validated feasibility: **Smart Patient Room prototype** with IoT, Azure DT, blockchain logging, visualization
- Positioned DTs as dynamic, operational tools to enhance interoperability and data security in healthcare

Thanks for Attention!

Aitäh!