Towards Developing an Ontology for a Digital Twin in Battery Testing

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Abstract: Ontologies are of great importance in organizing and structuring domain knowledge towards interoperability and data integration in various fields, as provide a standarised vocabulary and a formal representation of relationships between concepts, which is essential for advancing data-driven applications. This paper presents the development of an OWL (Web Ontology Language) ontology for the battery testing field, creating the foundations for the development of a Digital Twin that will virtualize tests to be performed on battery cells and modules. It emphasizes the significance of the battery domain characterization and ontology definition as critical components in developing an effective Digital Twin for battery testing. An investigation of prior studies available in the literature was conducted, highlighting examples of ontologies such as SSN (Semantic Sensor Network) and SOSA (Sensor, Observation, Sample, and Actuator), which targets integration into the digital twin environments to enhance sensor data management and interoperability. The research also found hybrid ontologies, combining elements from existing ones and battery-specific Digital Twin architectures. The developed ontology was validated through a practical use-case by integration with cloud platform Microsoft Azure Digital Twins, converting the ontology from OWL to DTDL (Digital Twins Definition Language). This step completes the cycle as the proposed framework aims to create a robust and scalable Digital Twin environment that can be adapted to various battery testing scenarios, providing actionable insights from tests.

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1 INTRODUCTION

The incorporation of Digital Twins in sophisticated battery technologies offers a revolutionary method for testing and optimizing battery performance in the ever-changing landscape of battery technology (Naseri et al., 2023). A Digital Twin depicts a physical system, allowing for continuous monitoring, simulation and data analysis. When it comes to battery testing, a Digital Twin can greatly expand our comprehension of battery performance in different situations, thereby enhancing efficiency, reliability, and lifespan (Javaid et al., 2023).

The development of a Digital Twin for the battery testing domain involves several critical steps, starting with the definition of the ontology. This, establishes a structured framework for organizing and interpreting the diverse parameters and data fields associated with battery testing providing a vocabulary and set of relationships that describe the characteristics, behaviors, and interactions of the various elements within the battery tests. This standardized framework ensures consistency and interoperability across different data sources and analytical tools (Karabulut et al., 2024).

The groundwork needed to characterize the ontology involves the identification and cataloging of all relevant data assets required for the Digital Twin. This includes sensors, metadata, simulation models, among others. By mapping these, we created a detailed blueprint that outlines how data flows between different components of the Digital Twin, facilitating integration and efficient data management (Haller et al., 2017). This introduction sets the stage for a deeper exploration of these concepts, highlighting their importance in creating a reliable Digital Twin that not only mirrors the physical battery system but also provides actionable insights for optimizing battery tests.

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2 ONTOLOGIES IN DIGITAL TWIN DEVELOPMENT

2.1 Overview

The concept of Digital Twins represents a significant advancement in the field of batteries testing and development. By constructing a virtual replica, researchers will have the capability to virtualize a range of scenarios, thereby getting faster results. This chapter explores specific ontologies that support Digital Twin technologies within the context of battery systems. It discusses their current state and examines potential modifications that could facilitate more effective virtual testing of batteries. The adaptability and extension of these ontologies are important for the accurate representation and analysis of battery behaviors under various test conditions, thus contributing to more precise and reliable battery technology developments.

Digital Twin technologies for batteries may need the integration of complex relationships and rules derived from multiple data sources. The implementation of well-defined ontologies in these systems is crucial for achieving smooth interoperability and consistency on the designed data model. This approach ensures that the Digital Twins accurately reflect their real-world counterparts and provide meaningful insights that are essential for battery testing scenarios.

2.2 Literature Review

Originally developed for sensor data integration and IoT applications, the SSN (Semantic Sensor Network) and SOSA (Sensor, Observation, Sample, and Actuator) ontologies provide frameworks that can be particularly beneficial for batteries Digital Twins (Karabulut et al., 2024; Janowicz et al., 2019), as they describe sensors and measurements, crucial for monitoring battery conditions. (Bamunuarachchi et al., 2021). This integration allows for a more detailed and structured representation of sensor data, observations, and actions within the system, facilitating improved interoperability and data analysis capabilities. This dual ontology approach leverages the strengths of both to provide a comprehensive framework that supports advanced monitoring and control functionalities within the Digital Twin environment.

The IoT ontologies, such as those proposed on Digital Twins in cyber-physical systems, offer robust structures for integrating real-time data into Digital Twin environments (Steinmetz et al., 2018). These ontologies are designed to handle dynamic and complex data streams, which are common in battery operation and testing scenarios. Implementing these IoT ontologies in battery Digital Twins would facilitate the integration of sensor data, enhancing the Twin's ability to simulate and predict battery behavior under different conditions. The work by (Merkle et al., 2019) outlines an architecture for a Digital Twin specifically designed for battery systems. This architecture could guide the development of a specialized ontology that addresses the unique needs of battery testing, such as lifecycle management, degradation modeling and performance optimization.

Other usages of ontologies are found to describe physical components, their physical attributes, states in a system and the relation in between them use an ontology to describe physical parts of a plant, such as root, stem or leaf, and the ontology is then used to extract rules for decision making (Skobelev et al., 2020). An example in manufacturing is one using an ontology for CNC (Computer Numerical Control) machine tool that includes concepts such as Material, Personnel, Device, and Environment (Liu et al., 2020).

Recent research demonstrates the growing use of ontologies for integrating and managing complex data in various domains. A relevant example is one developed to address sensor uncertainties in autonomous vehicles, enhancing safety and reliability by structuring knowledge about sensor limitations and environmental impacts (Alharbi. and A. Karimi., 2023). Other, to improve data synchronization between SysML models and heterogeneous data sources, promoting consistency in systems engineering (Zhang. et al., 2023). These studies, along with others that apply ontologies to physical components and manufacturing processes (Skobelev et al., 2020; Liu et al., 2020), highlight the potential for a hybrid ontology combining IoT frameworks and battery-specific Digital Twin architectures to support advanced battery management.

For the specific needs of virtualizing battery testing, a hybrid ontology combining elements from both SSN/SOSA for sensor data handling and specific constructs from battery-focused Digital Twin architectures could be appropriate. It should include definitions of battery cells and modules, including physical and chemical properties, standardized descriptors for test conditions, procedures and expected outcomes, and descriptions of performance metrics such as energy capacity, charge/discharge rates, and efficiency.

3 BATTERIES CHARACTERIZATION

This work considered battery testing for three distinct use cases: Offroad and Industrial, Automotive and

Stationary applications. Each has its own distinct particularities and technical characteristics, therefore, it is relevant for the Digital Twin to specify the baseline for each use-case typical cell and module. Furthermore, each use case has unique requirements, which may result in different tests sequences or procedures. Additionally, this characterization boosts traceability, helping in the identification of faults specific to each use case and in compiling useful statistics. Such detailed tracking will enhance the capabilities of the Digital Twin, providing a more complete solution and opening doors for future and more effective analytics.

3.1 Offroad and Industrial Devices

Table 1 presents cell technical specifications and Table 2 summarizes at module level, for the Offroad and Industrial use-case.

Table 1: Cell Level Data.

Parameters	Description	Value
Capacity		280 Ah
Voltage		3,2V
AC Impedance Resistance(1KHz)		≤0.25 mΩ
Standard charge and discharge	Charge/discharge current	0.5 C/0.5 C
Standard charge and discharge	Cut off voltage of charge/discharge	3.65V/2.5V
Maximum charge /discharge current	Continuous charge/discharge	1C/1C
Maximum charge /discharge current	Pulse charge/discharge (30s)	2C/2C
Charging Temp.		0°C∼55 °C
Discharging Temp.		-20°C∼55 °C
Chemistry/ Cell Type	Prismatic cell LIFEPO4	LFP

Table 2: Module Level Data.

Parameters	Value
Capacity	560 Ah
Voltage	6.4V
Configuration	2S2P
SOC Range	70-80

Table 3 displays measurements related to the battery cell testing procedure carried out during the incoming quality control phase. This step is performed to verify the compliance of the item with the manufacturer's datasheet and to collect information needed for predictive maintenance models. This information may serve to the Digital Twin as normal baseline values.

Table 3: Cell Testing Data in Control Phase.

Parameters	Value
Resistance Pre-Charge	0.35 mΩ
Resistance Post-Charge	0.15 mΩ
Capacity Residual	218.01 Ah
Capacity Tot	621 Ah
Impedance	0.105 mΩ
OCV V	3.295

3.2 Automotive Devices

Table 4 presents essential technical requirements for batteries intended for use in the automotive sector. These specifications are crucial to ensure that the batteries not only meet performance and safety expectations but also facilitate effective integration with vehicle electrical systems.

The criteria listed include the operational voltage range, which significantly varies from 90V to 450V to accommodate different types of vehicles. Additionally, a usable energy capacity ranging from 30 kWh to 100 kWh is specified, which is fundamental in determining the vehicle's range under various driving conditions.

Another key feature outlined in the table is the rapid charging performance, allowing the battery to reach 80% capacity in just 20 minutes—a critical characteristic for market acceptance of electric vehicles. These parameters not only reflect the direct technical needs of electric vehicles but also highlight the challenges associated with designing and testing battery systems that must be robust, efficient, and capable of handling the dynamic demands of modern electric mobility.

3.3 Stationary

Stationary or Battery Energy Storage Systems (BESS) considered for this work use a modularization approach where multiple modules are interconnected to reach the desired energy requirements. Currently it uses a minimum of three modules which can deliver usable energy up to 7.5 kWh. It can be further extended output up to 15 kWh by connecting seven modules. The modules utilize cylindrical cells of 18650 format and can be operated in a wide range of temperature (-15 and 55°C). Table 5 and Table 6 shows the cell and module level data specifications,

Table 4: Cell and Module Data.

Parameter	Value
Chemistry	LFP
Nominal operation voltage range	90V-450V
Usable Total Energy Capacity	30 kWh - 100 kWh
SOC of operation range	0%-80%
Fast charging performance	0%-80% in 20min./1.7C
Peak discharge power	200kW
Temperature operating range	Charge: -20°C and 55°C Discharge: -30°C and 55°C
Storage temperature range	-40°C ≤ 60°C
Lifecycle of application	160.000 km 1100 full cycles
Battery Pack Weight (1pack)	≤599kg
Energy Density - Pack	≥201Wh/kg
Energy Density - Module	≥281Wh/kg
Power Density – Pack (1C)	≥201Wh/kg
Power Density – Module (1C)	≥281Wh/kg

respectively.

Table 5: Cell Level Data.

Parameter	Value
Cell model	TerraE 30E
Cell chemistry	Li-ion NMC
Format	18650 Cylindrical
Voltage range	3.2∼4.08V

4 ONTOLOGY DEVELOPMENT FOR BATTERY TESTING

After collecting all relevant data so far for the detailed modelling of the problem within the battery testing domain, the next step was to create the ontology. For that, Protégé was used (Stanford Center for Biomedical Informatics Research, 2016), which is a comprehensive, free, open-source ontology editor and knowledge management system. It supports various ontology languages, including Web Ontology Language (OWL), facilitating the creation, manipulation and sharing of complex knowledge structures. It also features a user-friendly graphical interface that allows for design, visualization, and testing of ontologies, which makes it an ideal tool for modeling detailed ontological structures that define the relationships and properties of entities within specific domains.

In order to create an ontology ((Marques, 2024), four components are essential: Classes, Relationships, Properties and instances (also known as Individuals). In the following sub-section, these four components will be explained and detailed.

Table 6: Module Level Data.

Parameter	Value
Nominal Voltage	51.4V
Nominal energy	3.3 kWh
Usable energy	2.5 kWh
Charging current (max.)	29 A
Discharging current (cont.)	30 A
Discharging current peak (3s)	40 A
Depth of discharge (DoD)	≤79%
Charge operating temperature range	0 and 45ºC
Discharge operating temperature range	-15 and 55ºC
Internal protection of casing	IP20
Certification	IEC62619/VDE-AR-E2510-50/CE/UN38.3

4.1 Class

Being a Class, in the context of ontology design, a fundamental concept that represents a set of objects or instances sharing common characteristics or attributes, within this work, the following Classes were identified:

1. Components;
   a. Cell;
   b. Module;
2. Test;
3. Test Bench;
4. Test Procedures

Components are the entities that will be tested, and Cell and Module are a subclass of Components. The class Test, as the name suggests, was created to characterize the test that will be performed on a Component. The same logic applies to the classes Test Bench and Test Procedures.

4.2 Properties

Properties describe attributes or characteristics of the classes, defining specific aspects of the class instances, such as measurements, conditions, or descriptive elements as well as their data types, enabling a more detailed and structured representation of the data within the ontology. Figure 1 displays all the properties relevant to each class considered within this work. Since both Cell and Module are subclasses of the class Component, they share all data properties present in the Component class in addition to each specific properties. The Test class contains two main data categories: test properties and test telemetry. Test properties are important for defining a test with parameters such as Test Type and Test Procedure ID. Test telemetry considers parameters such as Time and Current, being responsible for recording the outputs of each test. Telemetry data is the only dynamic data among the properties.

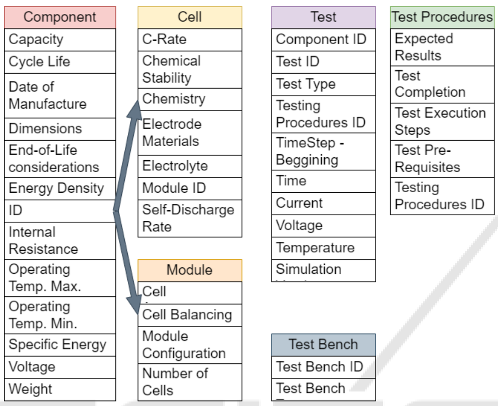

Figure 1: Properties of each class.

4.3 Relationships

Relationships describe how classes and instances are connected, defining the associations and dependencies between entities and helping to create a structured and meaningful representation of the data and comprehensive understanding of the domain. Within this work, the following relationships have been identified: **Belong**, that indicates that one entity is a part of another, **Contains**, shows that one entity includes another, **Made in**, specifies the location or environment where an activity takes place and **Made to**, defines the target or subject of an activity.

4.4 Constraints

Constraints specify conditions that must be met for a property (such as object or data properties) or a relationship to hold true for a particular ontological element, such as cardinality restrictions, which determine how many times a property can be used, and value restrictions, which define the types of values a property can accept. Together, constraints ensure that relationships between entities within the ontology remain coherent and logical. In our ontology, the following constraints were designed:

- **Constraint 1 (Test).** Each Test must include one Component (Cell or Module), one Test Procedure and one Test Bench;
- **Constraint 2 (Components).** Each Component must be classified wither as Cell or Module;

Since OWL is a declarative language, it doesn't allow conditional logic, so other potential constraints have been left out for this phase of the work, such as ones specifying ranges for data properties depending on the use-case, or depending on the test performed.

4.5 Instantiation and Validation

Instances represent concrete application examples of the classes defined in the ontology. They give real case scenarios to the abstract concepts and relationships. By creating instances, the accuracy and consistency of the ontology can be tested, ensuring that the defined classes, properties and relationships will model the real-world entities and their interactions. As an example, an instance of the class "Cell" might be a specific type of cell used in a battery test, while an instance of the class Test could be a particular test conducted on a cell. This validates the ontology's structure and functionality, verifying that all necessary elements are correctly represented and interconnected. Figure 2 displays an instance of the class "Cell" named "Cell 1".

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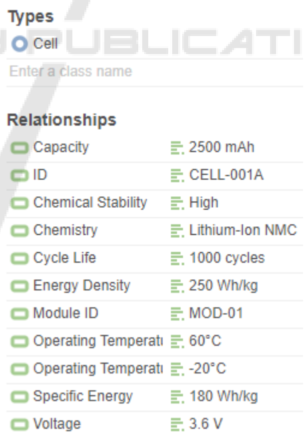

Figure 2: Instance of class "Cell".

As shown in Figure 2, the properties attributed to the cell class have been populated with real values creating an instance of the class "Cell".

By creating Instances, Protégé also allows to organize the created structures on a schematic manner, as seen in Figure 3. Here, an instance of the class "Module", contains "Cell 1" through "Cell 4" that are instances of the class "Cell".

Figure 4 illustrates "Preconditioning Test 1", as

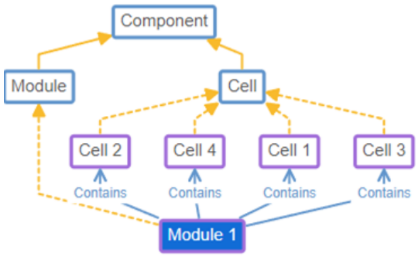

Figure 3: Graphical Representation of the Ontology: An Instance of the ”Module” Class Named ”Module 1”.

an instance of the class Test, that belongs to the ”Test Procedures 1”, an instance of the class ”Test Procedures”, which was performed in the ”Test Bench 1”, an instance of the Test Bench class and was made to ”Cell 1”, an instance of the class ”Cell”.

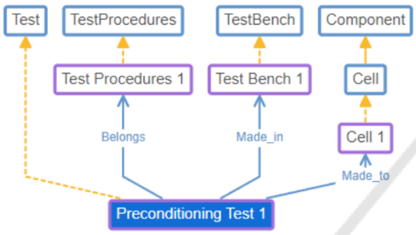

Figure 4: Representation of the Ontology: An instance of the ’Test’ Class as ’Preconditioning Test 1’.

The instantiation of classes validates the ontology, as it creates scenarios that test the model and ensures its suitability for the domain it represents. The definition of the ontology provides a structured and comprehensive framework for representing the battery testing domain with the entities, properties, and relationships.

5 FROM OWL ONTOLOGY TO A CLOUD PLATFORM - A CASE STUDY WITH MICROSOFT AZURE DIGITAL TWINS

Integrating ontologies with cloud platforms such as Microsoft Azure Digital Twins provides a scalable, flexible and interoperable environment for battery systems. This chapter focuses on incorporating the OWL ontology within Azure Digital Twins, emphasizing the process of converting the ontology from OWL to Digital Twins Definition Language (DTDL), which is the standard modeling language used by Azure Digital Twins.

5.1 Azure Digital Twins and Digital Twins Definition Language (DTDL)

Azure Digital Twins is a comprehensive cloud-based platform designed for building digital replicas of physical environments. It uses DTDL ((Marques, 2024)), which is a JSON-based modeling language designed for defining Digital Twin models, properties, telemetry and relationships in a machine-readable format. The language supports the integration of diverse standards, enabling interoperability across Digital Twin environments. Through DTDL its possible to define complex models that accurately represent battery components, such as cells and modules, and their respective properties, including voltage, temperature and state of charge. This provides a robust framework for modelling complex systems and enhancing their performance through real-time data integration.

5.2 From OWL to DTDL

To integrate the developed ontology within Azure Digital Twins, it had to be converted from the OWL format to DTDL, using a manual process that involved several key steps to ensure the Digital Twin models remain accurate and consistent with the original ontology. There are also available free tools to help this process (Kevin Hilscher, 2020).

The initial step was to identify the core entities and relationships in the OWL ontology that need to be represented in DTDL. In this work, these were ”Cell,” ”Module,” ”Test,” ”Test Bench,” and ”Test Procedures,” as well as their associated properties and relationships, such as ”Contains,” ”Belong,” ”Made in,” and ”Made to.” Each OWL class is translated into a corresponding DTDL model. For instance, the ”Cell” class in OWL becomes a DTDL model that specifies properties relevant to a battery cell, such as voltage and temperature, formatted in a JSON-like structure as shown in Figure 5.

In this convertion, properties defined in the OWL ontology, such as those for the ”Cell” class, were mapped to equivalent DTDL properties or telemetry, ensuring that each property retains its intended data type and functionality. Relationships in the OWL ontology, like the one indicating a ”Module” contains ”Cells,” were represented in DTDL using the ”Relationship” type, maintaining the logical connections and dependencies established in the OWL ontology.

```
{
    "@context": "dtmi:dtdl:context;2",
    "@id": "dtmi:FASTEST:dtmi:FASTEST:Test;1",
    "@type": "Interface",
    "displayName": "Test",
    "contents":[
        {
            "@type": "Property",
            "name": "ComponentID",
            "schema": "string"
        },
        {
            "@type": "Telemetry",
            "name": "Time",
            "schema": "time"
        },

        {
            "@type": "Relationship",
            "name": "MadeTo",
            "displayName": "MadeTo",
            "target": "dtmi:FASTEST:dtmi:FASTEST:Component;1"
        }]}
```

Figure 5: Example of JSON as part of the Test class in Digital Twins Definition Language (DTDL).

5.3 Deployment on Azure Digital Twins

Once the ontology was successfully converted to DTDL, the next step was to deploy to the Azure Digital Twins platform. This process involved uploading the DTDL models to the Azure Digital Twins instance using the Azure portal or through Azure SDKs and APIs. Upon deployment, these models form a digital representation of the battery testing system in the cloud, closely aligned with the structure defined in the OWL ontology, as illustrated in Figure 6.

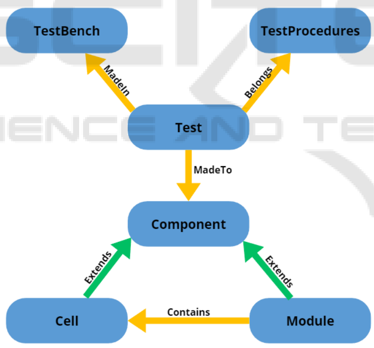

Figure 6: Ontology representation on Azure Digital Twins.

Subsequently, real-time data streams from IoT sensors and devices can be integrated in Azure Digital Twins. These data streams can be mapped to their corresponding DTDL telemetry properties, enabling continuous monitoring and analysis of battery performance across various test conditions. Additionally, custom logic and workflows can be implemented using other Microsoft Azure resources, such as Azure Functions, Logic Apps, or others, to automate actions, generate alerts and conduct calculations based on the Digital Twin data. For example, an alert could be set to trigger if the temperature of a battery cell exceeds a certain threshold, or a specific test procedure could be initiated automatically.

5.4 Advantages of Cloud Integration with Azure Digital Twins

Integrating the battery testing ontology with Azure Digital Twins provides several benefits. It enables real-time monitoring and feedback, which allows for proactive maintenance and more responsive decision-making. By continuously ingesting data from IoT sensors and physical devices, the Digital Twin environment remains dynamically updated, reflecting the latest conditions and states of the battery systems during tests. Furthermore, the use of Azure's advanced analytics tools may enhance the predictive capabilities of the Digital Twins, allowing more precise predictions about battery degradation patterns, performance optimization opportunities and potential failures, thus, enabling more efficient and targeted interventions during the testing stages. Additionally, the scalable infrastructure of Azure ensures that the digital twin environment can handle increasingly complex and large-scale battery testing systems. This scalability makes the solution both cost-effective and future-proof, accommodating growth and evolution in battery technology and testing requirements.

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6 CONCLUSIONS AND FUTURE WORK

Ontologies are crucial in Knowledge Engineering as they provide a structured framework for representing and organizing knowledge in a specific domain, contributing to the standardization and understanding across different systems, applications, and stakeholders, ensuring consistency and reducing ambiguity. Ontologies are the first step towards interoperability between different systems and organizations, driving to an effective and uniform data interpretation among all. This work has enabled the development of an Ontology in a standardised format for the field of battery testing. The literature review identified some Ontologies aimed at Digital Twins development, but none for the area of battery testing. As such, this work will fill the gap identified. The development of the Ontology using a standardised format makes it agnostic and applicable to different use-cases. Furthermore, practical steps were taken to validate the applicability and flexibility of the ontology, through creating instances and integrating with Microsoft Azure Digital Twins platform. The conversion from OWL to DTDL leverages Azure's cloud capabilities. This framework facilitates data integration and management, from raw sensor data to user-selected tests, ensuring efficient communication between physical and virtual testing environments. This cloud-based Digital Twin will continue to support ongoing innovation in battery technology, providing a flexible platform, adaptable to various contexts and technological environments.

This research establishes a foundational ontology for Digital Twins in battery testing. Nevertheless, being this an ongoing work, it is expected that future efforts will focus on consolidating the developed ontology, through concrete specification of all Tests, Test Procedures or other domain specifications not identified yet. This groundwork will allow further integration of real-time data streams from physical battery test benches, ensuring interoperability and validating the applicability of the ontology via Microsoft Azure Digital Twins cloud platform. These advancements will help create a more robust, adaptable, and comprehensive Digital Twin environment for battery testing, driving innovation and optimization in this critical field.

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