A Domain-Agnostic Virtual Choreography Framework for Digital Twins: an Oil Spill application

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***Abstract*—Digital Twins (DTs) for the ocean are rapidly emerging as essential tools for understanding, forecasting, and managing environmental phenomena. However, most existing DT visualization solutions are tightly coupled to specific platforms and lack semantic coherence and interoperability—challenges that are particularly critical in federated and distributed DT systems. Furthermore, visualizing dynamic and spatio-temporal behaviors, such as oil spills, across multiple rendering environments remains a complex, platform-dependent task.**

In this paper, we present VChor, a domain-agnostic virtual choreography framework designed to address these limitations. Our approach integrates model-driven engineering, semantic web technologies, and platform-independent representations to support the declarative specification of behaviors and visual mappings. A single VChor instance describes spatio-temporal dynamics and associated actions, and can be interpreted by multiple visualization engines (e.g., Unity3D and CesiumJS) without the need for code recompilation or platform-specific programming.

We demonstrate our approach through a real-world oil spill monitoring use case, developed in the context of the ILIAD H2020 project, and encapsulated within a modular Application Package. This package automates the generation, validation, and transformation of virtual choreographies from raw data to platform-specific outputs. The framework promotes interoperability, reusability, and scalability, while supporting FAIR principles in environmental Digital Twin workflows.

The findings highlight VChor's potential to streamline scenario modeling, enable cross-platform visualization, and support decision-makers with accurate, flexible, and reusable visual representations of ocean dynamics.

***Index Terms*—virtual choreographies, immersive environments, digital twins, ocean data, interoperability**

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I. Introduction

The preservation of ocean ecosystems is a global priority, increasingly supported by Digital Twin (DT) technologies that integrate real-time observations, historical records, simulations, and interactive visualizations. DTs have the potential to offer stakeholders—ranging from scientists and policymakers to service providers—timely, actionable insights into complex marine phenomena, from coastal erosion to anthropogenic disasters [12, 6].

Among such threats, oil spills remain a pressing environmental and socioeconomic concern. In 2024 alone, approximately 10,000 tonnes of oil were lost to the oceans through tanker incidents [16]. Responding effectively to such events requires robust decision-support tools capable of representing the evolving behavior of an oil spill with spatial and temporal accuracy.

Current DT visualization tools tend to remain platform-bound, requiring customized code to transform simulation data into visual outputs for each target engine. This coupling limits modularity, reusability, and adaptation to new contexts [13].

To address these challenges, we propose a domain-agnostic virtual choreography (VChor) framework for modeling and visualizing dynamic geospatial phenomena. VChor enables the declarative specification of behaviors, entities, and events, abstracted from rendering logic, and interpreted by diverse platforms such as Unity3D and CesiumJS. It leverages model-driven engineering and semantic technologies to create reusable, interoperable choreographies aligned with FAIR principles (Findable, Accessible, Interoperable, Reusable).

We evaluate our framework through a real-world oil spill simulation scenario, developed within the context of the ILIAD H2020 project, and packaged as a portable, modular Application Package. The approach demonstrates how VChor

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supports scenario authoring, cross-platform visualization, and data-driven decision-making.

The remainder of this paper is structured as follows: Section II reviews the state of the art; Section III presents the VChor methodology and architecture; Section IV details the oil spill use case; Section V discusses results and limitations; and Section VI outlines conclusions and future work.

II. State of the Art

A. Digital Twins interactive visualizations

DTs enable continuous and timely ocean monitoring by integrating heterogeneous data sources into coherent, interactive representations of marine phenomena. A typical DT pipeline concludes with a visual user interface, where interactive visualizations support exploration, analysis, and evidence-based decision-making [22, 8, 14].

In the context of oil spill detection and monitoring, numerous data sources are employed. These include remote sensing technologies (e.g., Synthetic Aperture Radar - SAR), unmanned aerial vehicle (UAVs), and simulation models capable of generating synthetic data reflecting complex environmental conditions [23, 16].

To facilitate the integration of such diverse sources, the geospatial community has established several data representation standards and technologies, many of which adhere to the FAIR principles. Examples include:

- SpatioTemporal Asset Catalog (STAC): Enables standardized indexing and retrieval of spatio-temporal geospatial assets [19].
- NetCDF: A widely adopted format for multidimensional scientific datasets, offering platform neutrality and interoperability [17].
- GeoTIFF, Shapefiles: Support georeferenced raster and vector data for integration into GIS platforms [18, 7].
- Zarr/GeoZarr, Parquet/GeoParquet, and Cloud-Optimized GeoTIFF (COG): Designed for scalable, cloud-native data handling [27].
- CoverageJSON, GeoJSON and KML: Enable lightweight, web-compatible data exchange [3, 4, 11].
- Ocean Information Model (OIM): Facilitates interoperability between datasets and services in marine science [1].

While these standards and technologies excel in describing and exchanging geospatial data, they were not designed to model dynamic relationships, temporal behaviors patterns, or interactions. In the context of oil spill scenarios, these events include various behavioral patterns and interactions, from weathering processes (eg. transport and degradation) to environmental and socioeconomic entities interactions [21]. This limitation becomes particularly evident in DT scenarios that require platform-independent behavior modeling and visualization of events such as oil spills.

Current DT implementations face key limitations [13, 15]:

- **Platform Dependency**: Visualizations are often tightly coupled to specific rendering platforms, hindering reuse and interoperability.
- **Semantic Inconsistencies**: Data pipelines frequently lack semantic consistency, complicating integration across diverse systems.
- **Behavior Modeling Constraints**: Many existing solutions do not support platform-independent behavior modeling, a crucial feature in federated digital twin ecosystems.

B. Virtual Choreographies

A virtual choreography is a high-level semantic model that is capable of encoding data about spatiotemporal behaviours, for visual representation purposes (such as the propagation of an oil spill) and independently of the rendering technology. This model is distinguished by its ability to abstract both the data and its associated behaviours, thereby facilitating flexible deployment across different rendering engines without the requirement for platform-specific programming. Virtual choreographies are predicated on the principles of model-driven engineering and semantic technologies, to enable the transformation of diverse scientific datasets into reusable high-level semantic model instances. These instances can then be interpreted and visualized in various environments through declarative mappings, ensuring consistency and adaptability.

In other fields, the concept of virtual choreographies has emerged as a method for specifying coordinated behaviors across systems. In virtual reality and education, they have been used for authoring tools and procedural training [5]. In storytelling, they enable interactive, platform-neutral narratives [10]. Multi-user applications have employed model-driven choreographies for synchronizing actions across virtual worlds [20]. In scientific workflows, choreographies have supported dynamic execution, rewinding, and replaying of process chains [26].

To address these gaps, we adopt and extend the concept of virtual choreographies to the domain of ocean Digital Twins. We propose a high-level, platform-independent model that decouples data representation from its rendering logic, thus supporting information modularity, semantic extensibility, and cross-platform visualization of dynamic spatio-temporal events.

III. Approach: A Domain-Agnostic Framework for Digital Twin Visualization

We propose a VChor domain-agnostic framework for developing interoperable, semantically rich, and platform-independent visualizations of spatio-temporal phenomena in Digital Twins (DTs). Grounded in model-driven engineering, VChor enables the declarative specification of behaviors and interactions, decoupled from rendering logic and adaptable to diverse visualization platforms. Designed for reusability across domains and use cases, the framework supports the creation of standardized, high-level representations of dynamic geospatial data, aligning with the goals of federated and environmental digital twins.

A. Foundations and Design Principles

The VChor framework is founded on three core design principles:

- **Model-Driven Engineering (MDE)**: by separating concerns between data, behavior logic, and presentation, MDE enables the transformation of high-level semantic models into platform-specific implementations without manual coding.
- **Semantic Technologies**: formal ontologies and descriptors are used to enrich datasets with contextual meaning, enabling pattern recognition, validation, and interoperability across systems.
- **Platform Independence**: the rendering logic is decoupled from the behavior model. This allows choreographies to be interpreted by different engines (e.g., Unity, CesiumJS) using the same underlying representation.

Together, these principles support FAIR-compliance, ensuring that VChor models are not only syntactically well-structured, but also semantically explicit, platform-independent, and aligned with best practices for data reuse and system interoperability.

The MDE approach supports reusability by enabling the separation of behavior logic from implementation details, allowing models to be easily adapted across platforms or scenarios without rewriting code.

The incorporation of semantic technologies enhances findability and interoperability by embedding formal, machine-readable descriptions (e.g., ontologies, controlled vocabularies) into the choreography structure, thus enabling discovery, integration, and automated reasoning across systems.

Finally, the commitment to platform independence ensures accessibility and broader dissemination of DT content by allowing the same high-level model to be interpreted by diverse visualization tools—whether browser-based or immersive—without technical modification.

Taken together, these foundations make VChor particularly well-suited for federated and distributed DT environments, where data and behaviors must be discoverable, shareable, executable, and reusable across heterogeneous infrastructures and user communities.

B. VChor Framework Architecture

The following modular architecture can be considered, composed of four main components:

- **Conceptual Model**: Defines the metadata vocabulary and structure for entities, behaviors, and actions.
- **VChor Generator**: A pluggable tool that produces platform-neutral choreography models. It includes:
  - Segmentation Plugins: Divide data into temporal frames.
  - Pattern Plugins: Detect recurring behavior patterns.
  - Handler Plugins: Map data and behavior elements into the choreography structure.
- **Model Transformation Layer**: Converts abstract choreographies into platform-specific instructions using transformation templates (e.g., Jinja2). This layer adapts to target engines like Unity or Cesium by applying associated rendering logic.
- **Model Validation**: Assures the compliance with the conceptual model.

Each component can be extended or replaced to suit specific domain needs, ensuring flexibility and scalability across applications.

C. Conceptual Pipeline

To operationalize the VChor framework, it is relevant to include additional elements, services and tools, such as, data acquisition, data preparation and visualization. The following approach can be conceptually described as a structured processing pipeline comprising five key stages (Fig. 1):

- **Data Acquisition**: Heterogeneous environmental datasets (historical, real-time, or forecasted) are collected from sources such as remote sensors, simulations, and in situ measurements.
- **Data Preparation**: Datasets are harmonized and semantically enriched. Preprocessing ensures syntactic compatibility and consistency.
- **Choreography Modeling**: High-level spatio-temporal behaviors and events are represented using the VChor conceptual model (entities, properties, behaviors over time) that will be transformed, via VChor generator, to produce a platform-neutral choreography file.
- **Model Validation and Transformation**:
  - **VChor Recipe**: a semantic metamodel of the VChor schema, that defines supported vocabulary, entities, and actions, serving as both documentation, validation and a transformation reference for platform-specific implementations.
  - **Platform Recipe**: consists in a platform specific data interface, that contains relevant choreography elements according to the platform.
  - **Platform-specific formats transformation**: generates platform files, via transformation languages, by making connections between agnostic choreography models and platform recipes.
- **Visualization and Interaction**: The finalized choreography is rendered in visualization tools, such as, 2D/3D interactive environments, that may allow user exploration, scenario simulation, and decision support.

This pipeline abstracts the lifecycle of DT visualization by encapsulating the full process — from raw, heterogeneous data ingestion to semantically driven rendering — into modular, generalizable stages. Each stage fulfills a key function that is present in virtually all digital twin workflows, ensuring that the pipeline is reusable across domains, compatible with diverse technologies, and aligned with the goals of interoperability and scalability in federated DT ecosystems.

D. Evaluation Criteria and Rationale

We evaluate the VChor framework against five key criteria drawn from software engineering and DT literature:

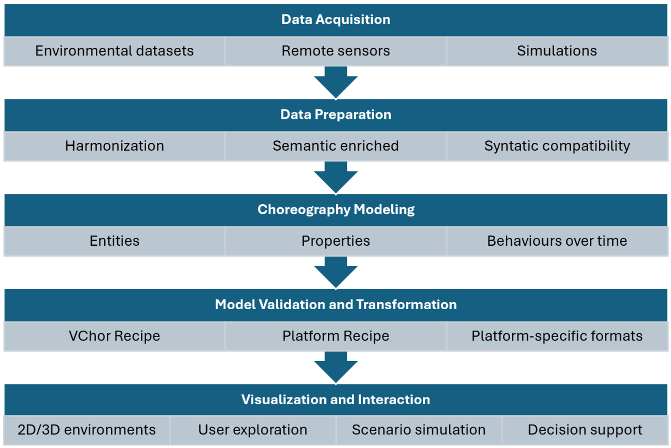

Fig. 1. Conceptual Pipeline Diagram

- **Interoperability**: The same choreography can be interpreted by multiple platforms without modification, focusing on runtime and rendering compatibility.
- **Flexibility**: The framework adapts to various domains, data types, and visualization requirements.
- **Scalability**: VChor handles large-scale datasets and increasing behavioral complexity through modularity and automated transformations.
- **Reusability**: Behavioral and visual patterns are defined declaratively and reused across scenarios, decoupled from platform-specific implementations.
- **Declarativity**: Users define behaviors using structured, high-level JSON schemas without imperative code.

The evaluation criteria adopted in this work—drawn from established practices in software architecture, model-driven engineering, visualization systems, and digital twin research—are well supported by the scientific literature [2, 26, 24, 9]. While these criteria align with the core dimensions of the FAIR principles, they also extend beyond data-centric concerns by addressing execution-time behavior, visual representation capabilities, and deployment feasibility within federated and heterogeneous digital twin environments. In particular:

- **Interoperability**: extends the FAIR view of interoperability into the realm of implementation-level compatibility, which is essential for distributed and federated digital twin deployments.
- **Reusability**: reflects a software architectural perspective on reusability that complements the FAIR focus on data management and governance.

IV. Application Scenario: Virtual Choreographies for Oil Spill Monitoring

To demonstrate the applicability and flexibility of the VChor framework, we conducted a study using a real-world *oil spill simulation scenario* developed within the context of the *ILIAD H2020 project*. The scenario involves transforming historical `NetCDF`-based spatio-temporal datasets into platform-independent virtual choreographies and rendering them across heterogeneous environments.

A. ILIAD Context and Application Package Design

The ILIAD project aims to create a federated European Digital Twin of the Ocean, emphasizing standardization, data sharing, and reusability. Within this ecosystem, we designed a VChor-based *Application Package* to encapsulate the oil spill use case. This package includes:

- **Application Package Document:** Defined using the *Common Workflow Language (CWL)*, it specifies inputs, outputs, tools, and metadata.
- **Application Package Container:** Implemented in *Docker*, ensuring a reproducible environment for execution across local or cloud-based infrastructures.

B. Pipeline Representation

The developed oil spill Application Package prototype is able to generate virtual choreographies of oil spills in the ocean, given inputs such as location, radius, time, type of oil, and others. This Application Package is a multi-step workflow where each step performs a specific task. The implemented processing components can be mapped in the following sections, that corresponds to the Conceptual Pipeline (Fig. 1) presented in the previous section.

1) Data Acquisition:

- **Step_point2bbox** takes a geographic location and radius and returns a bounding box.
- **Step_bathymetry** takes a bounding box and returns the area's bathymetric data.
- **Step_generate_model** processes core inputs (oil type, location, time, number of samples, and simulation duration) to generate a (2D+time)/(3D+time) NetCDF file simulating the oil spill across a given timeframe and location.

2) Data Preparation:

- **Step_extract_particles** extracts particle data from the NetCDF file and outputs it in STAC or GeoJSON formats.
- **Step_crop_frames** takes the particle data and segments it into temporal frames for further processing.
- **Step_generate_contours** generates contour shapes representing oil spill boundaries for user-defined particle densities.
- **Dir2files** is a utility step that converts a directory into a list of individual files.
- **Json_append** is a utility step that merges multiple JSON files into a single output.
- **Step_metadata_2stact2** adds necessary metadata to STAC-compatible output files.
- **Step_2stac2** aggregates all result files and compiles them into a complete STAC catalog.

3) Choreography Modeling: The VChor model follows a standardized JSON-based format comprising several interrelated components. The `@context` section defines the vocabulary and semantic references drawn from sources like schema.org and xAPI registry, establishing the semantic foundation. Within the @definitions component, both static (@const) and dynamic (@state) properties of entities involved in the scenario are defined, enabling precise representation of the entities involved in the VChor, both conceptual and physical. The @behaviours component documents actions as statements with actor-verb-object relationships, being heavily inspired by the xAPI specification. Finally, the @choreography component presents a chronological timeline of events and their associated behaviors, creating a temporal narrative. Complementing the VChor model, the VChor framework contains a generator, a validator and the recipe inference tool.

The Generator component produces virtual choreographies from the oil spill boundary files produced during the data preparation. Elements and behaviours can be added to the choreography without writing additional code. More complex operations can be supported using Python scripts that are connected to the generator as reusable plugins. The choreography generator not only supports a declarative style for virtual choreography creation but also allows generation templates to be exported as JSON files. This export capability enables templates to be easily reused across projects and integrated into automated workflows.

After generating the choreography, the validator is employed to assess compliance with the information model and the recipe inference tool is used to suggest appropriate recipes for the choreography, represented as a JSON schema.

4) Model Validation and Transformation: The Transformer component converts virtual choreographies into platform-specific representations using Jinja2 templates and data transformation plugins to define two distinctive translations between the generic virtual choreography to both the Cesium and Unity platforms, indicating additional platform-dependent parameters such as 3D models. Before applying the transformation, the tool validates the choreography against the associated recipe. Following the transformation, the tool compares the obtained platform choreography with the platform's recipe, finally saving the result in a JSON file.

5) Visualization and Interaction: In order to visualize the produced platform choreographies, GIS tools (Geographic Information Systems) [25] were used to model, integrate, and manipulate three-dimensional geospatial environments within graphics engines. In the context of this project, two different approaches were utilized: one using Cesium in JavaScript for web visualization and another using Unity3D for real-time simulation.

The web version, implemented with Cesium, prioritized a map-based visualization, allowing users to explore geospatial data interactively in a browser environment, with features such as terrain representation and object positioning. In contrast, the Unity3D version focused on simulating the dispersion of oil spills, emphasizing the geometric shape of the spill and how it evolved in response to intrinsic ocean variations such as waves, wind, and other environmental factors. This approach enabled a more realistic representation of how the oilspill spread over time rather than simply visualizing floating objects. By employing these two distinct methodologies, the project ensured a balance between data visualization and dynamic environmental simulation.

Both environments consume the same VChor instance, confirming its platform independence and flexibility.

C. Reusability and Declarative Behavior

Two choreography scenarios were tested: a static spill with nine time steps, and a dynamic spill with seventy time steps and a ship entity. The ship was included declaratively by changing the generator configurations without establishing new transformation logic. This demonstrates VChor's ability to separate behavior specification from rendering logic.

D. Integration with FAIR and Interoperability Goals

The Application Package supports FAIR principles:

- **Findability**: Metadata supports indexing and cataloging.
- **Accessibility**: Output bundles are self-descriptive and portable.
- **Interoperability**: Uses open formats (e.g., NetCDF, STAC, GeoJSON).
- **Reusability**: Templates and generation recipes are exportable.

V. Results and Discussion

The oil spill Application Package developed within the ILIAD framework demonstrates the potential of the VChor model to support interoperable and scalable visualizations across heterogeneous rendering platforms. Using a single choreography model, we successfully generated interactive visualizations in both Unity and CesiumJS, validating the framework's platform-agnostic nature.

A. Scenario Evaluation

Two representative scenarios were designed:

- A **static oil spill** with nine time steps (Fig. 2, Fig. 3)
- A **dynamic oil spill** with seventy time steps and a ship entity. (Fig. 4, Fig. 5)

Both scenarios were processed through the same pipeline. The ship in the dynamic scenario was added declaratively via configuration, requiring no additional programming. This confirms the framework's declarative and extensible design.

B. Platform-Specific Rendering

The final visualizations showed that the same VChor instance could be interpreted by:

- **Unity**: A real-time, 3D immersive simulation with environmental dynamics. (Fig. 2, Fig. 3)
- **CesiumJS**: A map-based web visualization optimized for interactive exploration. (Fig. 4, Fig. 5)

This confirms the model's platform neutrality and multi-stakeholder accessibility.

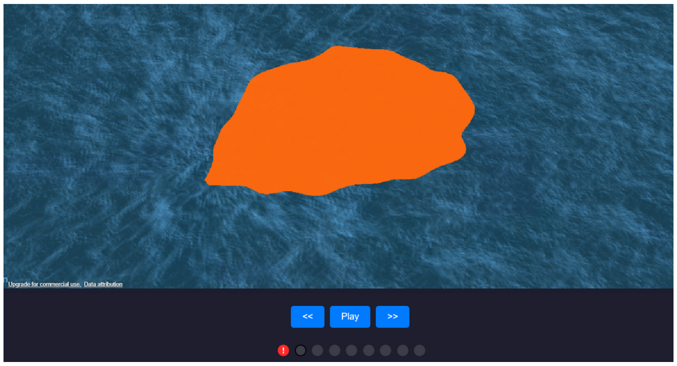

Fig. 2. CesiumJS static oil spill with nine time steps

Fig. 3. Unity static oil spill with nine time steps

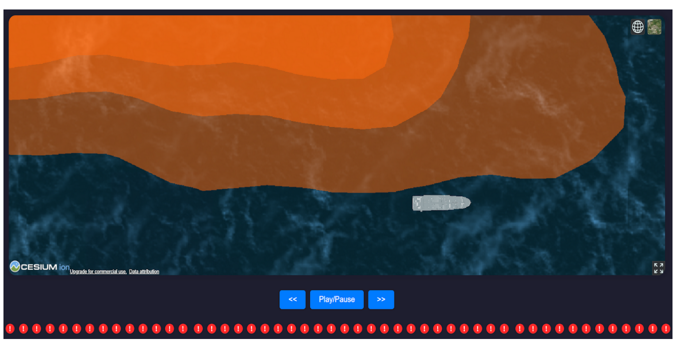

Fig. 4. CesiumJS dynamic oil spill with seventy time steps and a ship entity

Fig. 5. Unity dynamic oil spill with seventy time steps and a ship entity

C. Reusability and Modularity

Reusable behavior templates and transformation recipes allow new scenarios to be created or extended without altering the core logic. This modularity supports rapid scenario prototyping and cross-domain applicability.

D. Identified Limitations

Despite its strengths, several limitations remain:

- **Lack of a choreography catalog:** Limits the model's findability and accessibility.
- **Insufficient metadata:** Affects traceability and semantic richness.
- **Code-level coupling:** Generator and transformer tools are not formally packaged or cataloged, limiting interoperability.

Addressing these will enhance FAIR compliance and integration into broader DT ecosystems.

VI. Conclusions

This paper introduced *VChor*, a domain-agnostic virtual choreography framework designed to enhance the interoperability, reusability, and semantic expressiveness of Digital Twin (DT) visualizations. The proposed model and framework enable the declarative representation of spatio-temporal behaviors and visual mappings, abstracted from platform-specific rendering logic.

By leveraging model-driven engineering and semantic web technologies, VChor provides a structured approach to transforming complex environmental datasets into reusable, platform-independent choreographies. The framework supports cross-platform visualization, enabling the same choreography instance to be rendered in immersive (Unity) and web-based (CesiumJS) environments.

The approach was validated through a real-world oil spill scenario developed within the ILIAD project. Using an Application Package with a 14-step workflow, we demonstrated that stakeholders can interact with dynamic ocean data without programming, supporting FAIR principles and accelerating scenario development.

Despite these strengths, several limitations were identified:

- No choreography catalog exists, hindering discovery and reuse.
- Metadata is limited, reducing semantic traceability.
- Generator and transformer components are not yet formally packaged or portable.

Future work will focus on:

- Developing a choreography indexing and cataloging system;
- Enhancing metadata through RDF and SHACL;
- Modularizing tools into language-agnostic libraries for broader adoption.

Although demonstrated in the context of marine pollution, the proposed framework is applicable to other spatio-temporal phenomena such as ocean currents, shipping traffic, or plastic dispersion. The current approach presents a scalable and extensible solution for behavioral modeling in DTs, with potential to foster collaborative, cross-platform, and data-driven decision-making in marine science and other domains.

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