PURDUE UNIVERSITY

Onto-Graph: AI-Driven Framework for Ontology-Guided Clustering and Hierarchical Structuring in System-of-Systems Engineering

Sep 15, 2025

CENTER FOR INTEGRATED SYSTEMS IN AEROSPACE

Presentation Outline

Onto-graph framework for System-of-systems engineering

- Research Motivation
- Problem statement
- Proposed framework: Onto-graph
  - Ontology-guided Indexing
  - Hybrid Clustering
  - Application & Querying
- Example & Result
- Future works & Potential impact

Motivation - The Growing Challenge of Complexity in SoS

Why System-of-Systems Remain Hard to Engineer

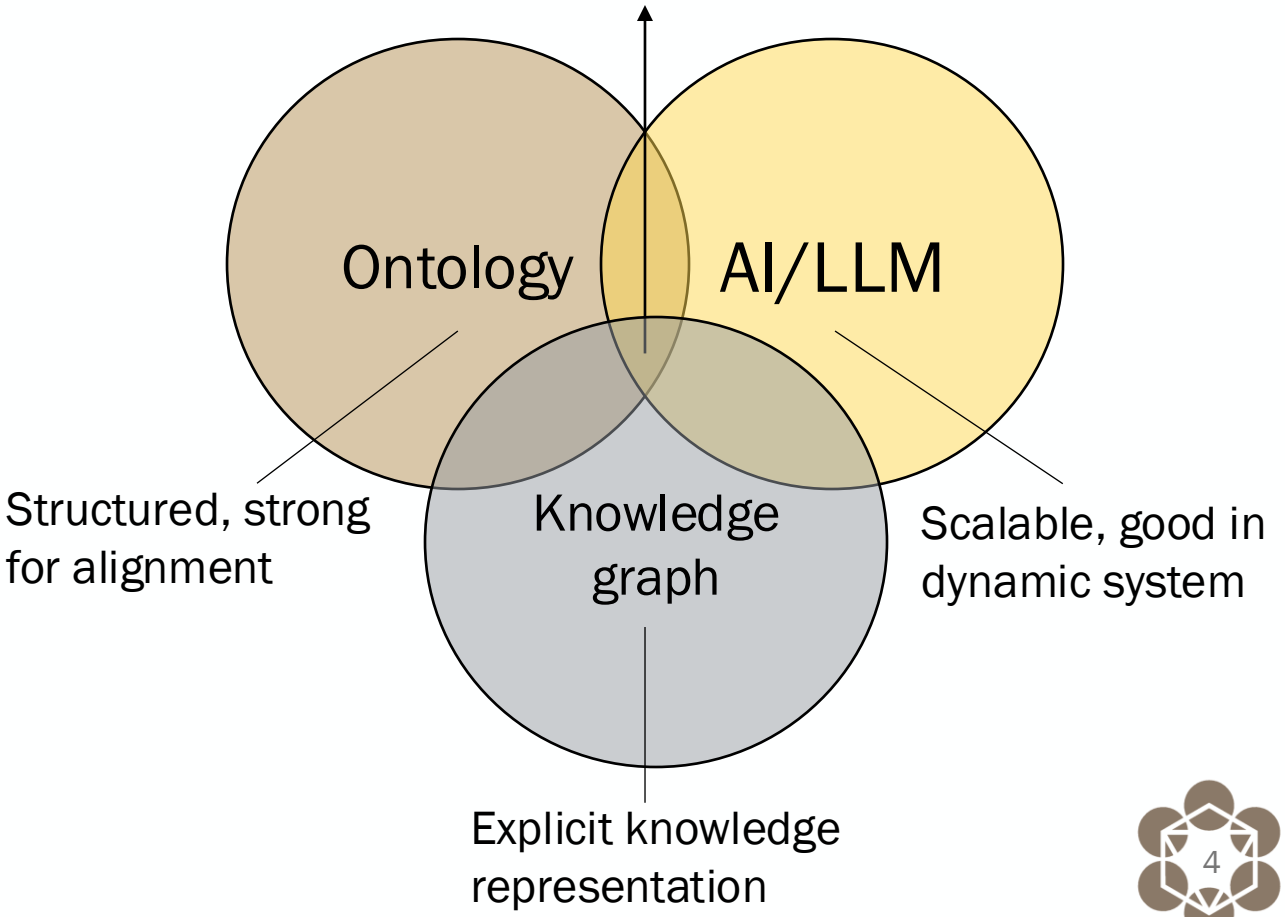
- Modern engineering increasingly involves **System-of-Systems** — independent subsystems that evolve dynamically.
- Traditional approaches (document-based SE, MBSE) struggle with **scalability, semantic alignment, and evolving terminology**.
- Example domain: **Urban Air Mobility (UAM)** — requires coordination across engineering, policy, infrastructure, and industry.
- Need for **adaptive, interpretable, AI-assisted frameworks** to manage complexity.

Problem statement

Daily pain points for system engineers

- Inefficient collaborations caused by inconsistent vocabulary
- Difficulty integrating unstructured data
- Managing Complexity at Scale
- Keeping Models Up-to-Date with Change
- Conflict and Discrepancy Detection in early stage of design
- No framework yet that:
  - Combines ontology's **semantic grounding** with AI/LLMs' **flexibility**
  - Provides **interpretable, scalable integration** for SoS
  - Adapts to evolving domains like **Urban air mobility**

Onto-graph: A hybrid framework combining ontology and LLM to assist SoS engineering



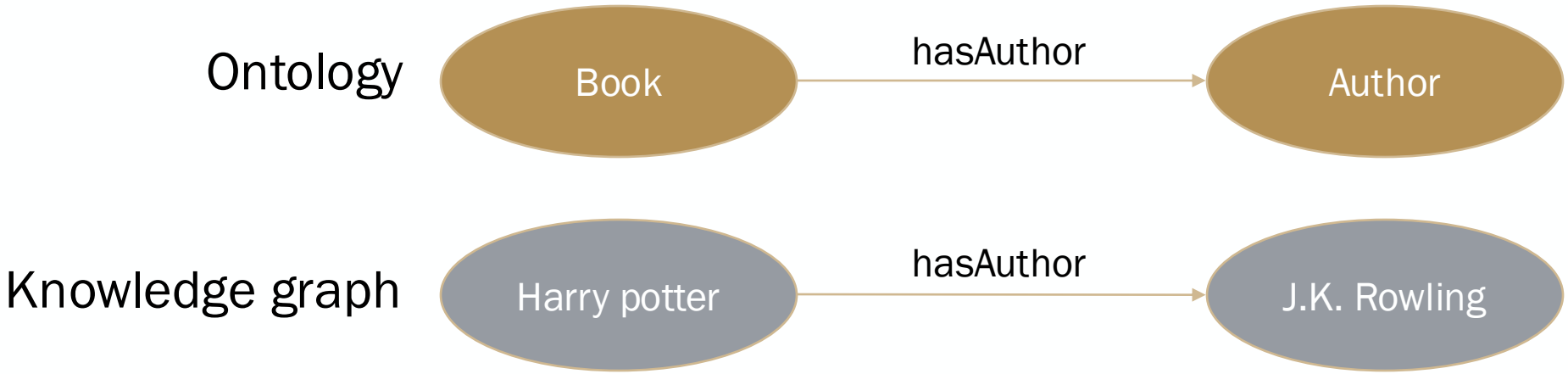
Background-Knowledge graph and Ontology

Ontology

- A formal vocabulary that defines concepts and their relationships.
- Ensures shared meaning across disciplines (e.g., “vertiport” vs. “aerodrome”).
- Acts like a dictionary + rulebook for systems engineering.

Knowledge Graph (KG)

- A network of entities (nodes) and their relationships (edges).
- Built from structured + unstructured data (reports, SysML, regulations).
- Provides a visual and queryable model of how systems connect.



Proposed methodology

Onto-graph approach

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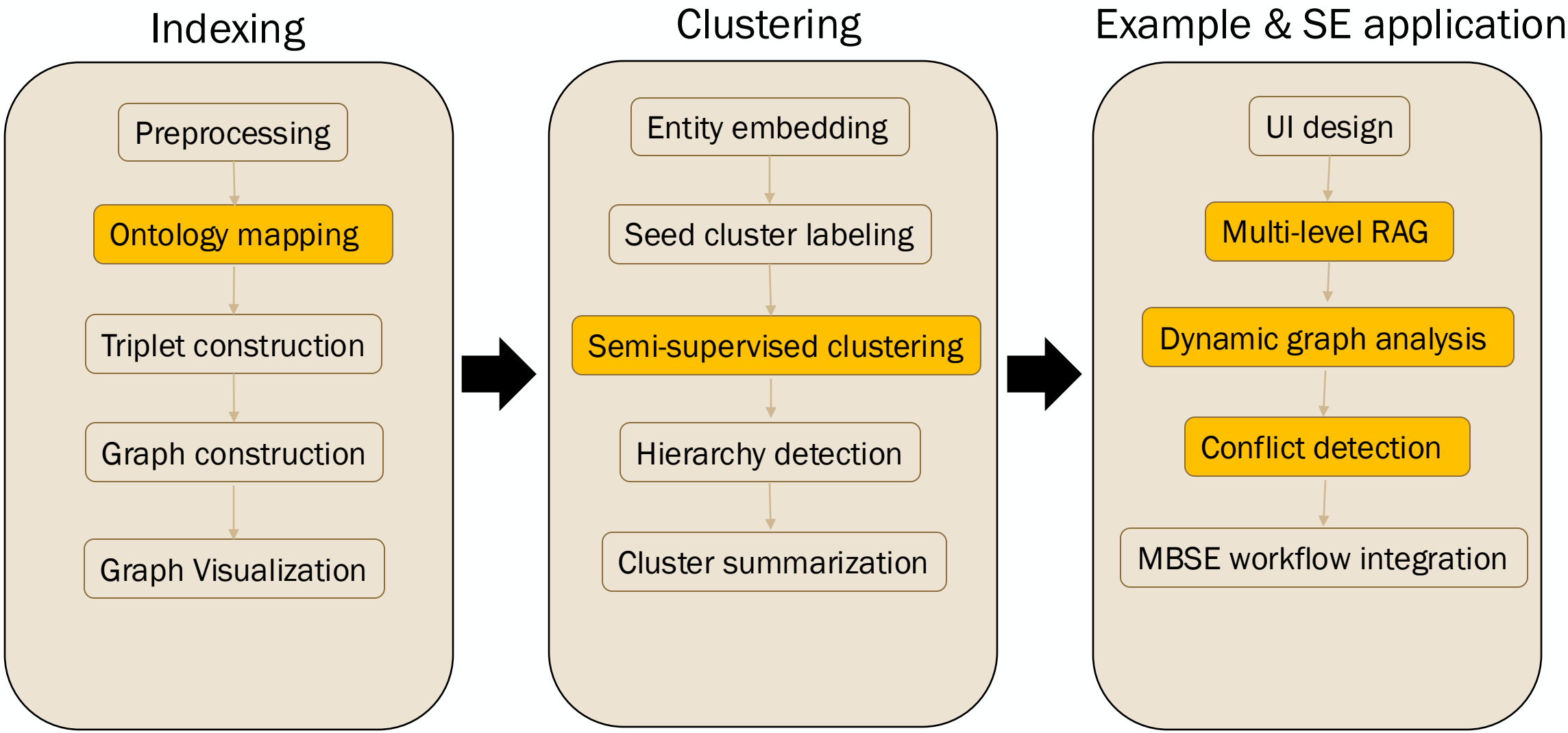
Onto-Graph Framework Overview

An Ontology-Guided AI Framework for SoS



Indexing - From Text to Knowledge Graph

Unify vocabulary and construct knowledge graph via LLM

- Heterogeneous sources ingested (reports, ConOps, policies, memos).
- Documents **chunked + embedded** for retrieval
- LLM extracts **entities** (systems, institutions, processes) & **relations** (natural language)
- Entities mapped to **ontology classes, merging canonical entities**
- Result: an **annotated directed graph** representing SoS knowledge

- Document chunking
- Prompt-tuning
- Chunk embedding

- Entity extraction
- Relation extraction
- Ontology mapping

- Canonical entity merging
- Conflict detection

- Final graph construction
- Graph visualization

Ontology mapping and entity merging

- UAM Infrastructure
  - Physical infrastructure
    - Vertiport system
    - Maintenance system
  - Software infrastructure
- UAM governance
  - Domestic governance
  - International governance

FAA Federal Aviation Administration(FAA)

UAM Vertipad Vertiports UAM Hangar

Ontology mapping and entity merging

- UAM Infrastructure — UAM Vertipad — Vertiports — UAM Hangar
  - Physical infrastructure
    - Vertiport system
    - Maintenance system
  - Software infrastructure
- UAM governance — FAA — Federal Aviation Administration(FAA)
  - Domestic governance
  - International governance

Ontology mapping and entity merging

- UAM Infrastructure
  - Physical infrastructure
    - Vertiport system ● UAM Vertipad ● Vertiports
    - Maintenance system ● UAM Hangar
  - Software infrastructure
- UAM governance
  - Domestic governance ● FAA ● Federal Aviation Administration(FAA)
  - International governance

Embedding comparison/LLM judge for identical entities

Ontology mapping and entity merging

- UAM Infrastructure
  - Physical infrastructure
    - Vertiport system ● UAM Vertipad ● Vertiports
    - Maintenance system ● UAM Hangar
  - Software infrastructure
- UAM governance
  - Domestic governance ● FAA ← Add to synonyms table for future look up
  - International governance

Clustering – Organizing SoS Knowledge

Multi-layered KG for system representation

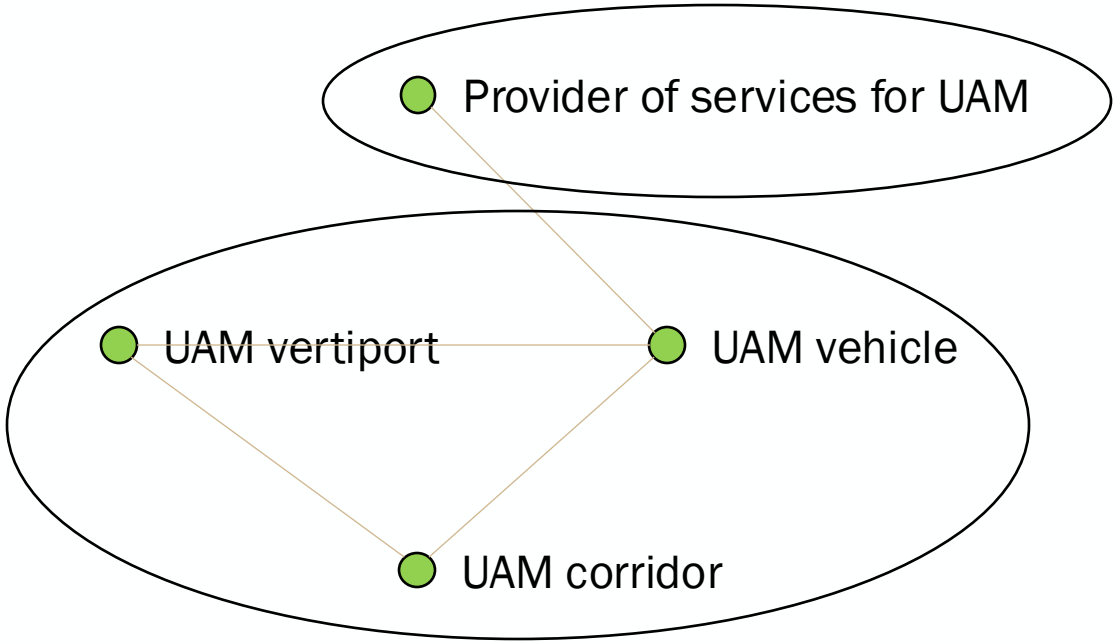
- Semi-supervised clustering with **ROPE framework (Resource, Operation, Policy, Economy)** + ontology.
- **Graph weights adjusted** based on ontology alignment & ROPE labels.
- **Leiden algorithm** optimizes modularity for meaningful groups
- Recursive clustering reveals **hierarchical abstraction**
- LLM generates **cluster summaries** for each community

ROPE labeling	Graph weight adjustment	Clustering	Cluster summaries
• Ontology-ROPE mapping • Entity ROPE labeling	• Adjust weight for ROPE labeled entities	• Leiden algorithm • Recursive until desired cluster size	• Multi-level cluster summarization

Unsupervised vs semi-supervised clustering

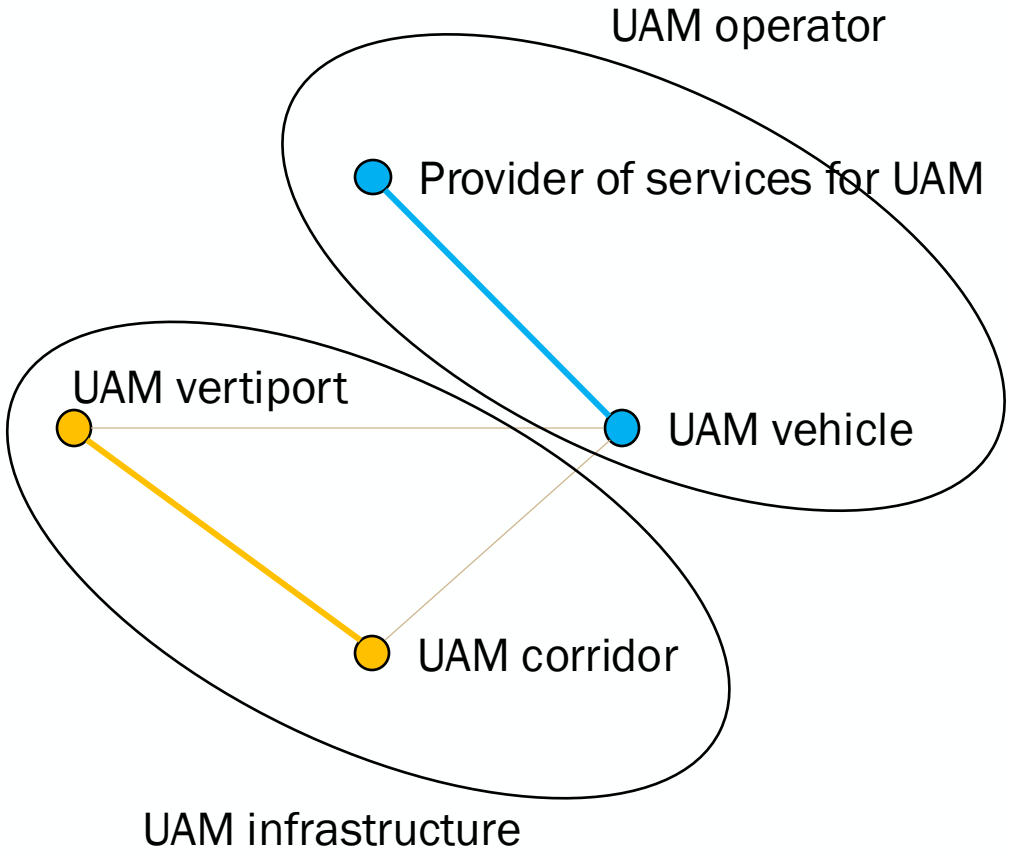
Unsupervised

- Based on pure graph structure
- Vague and general clusters



Semi-supervised

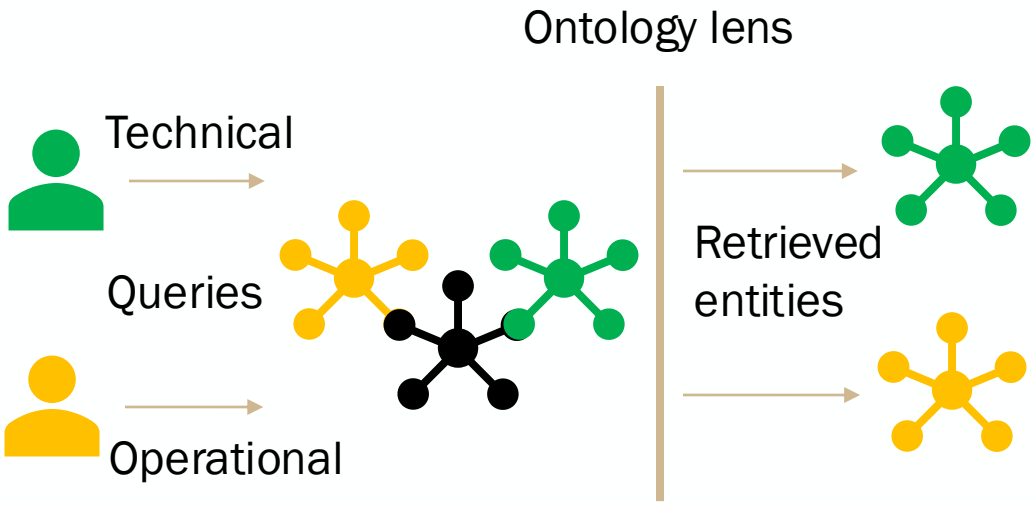
- Leverage prior knowledge
- Informative clusters

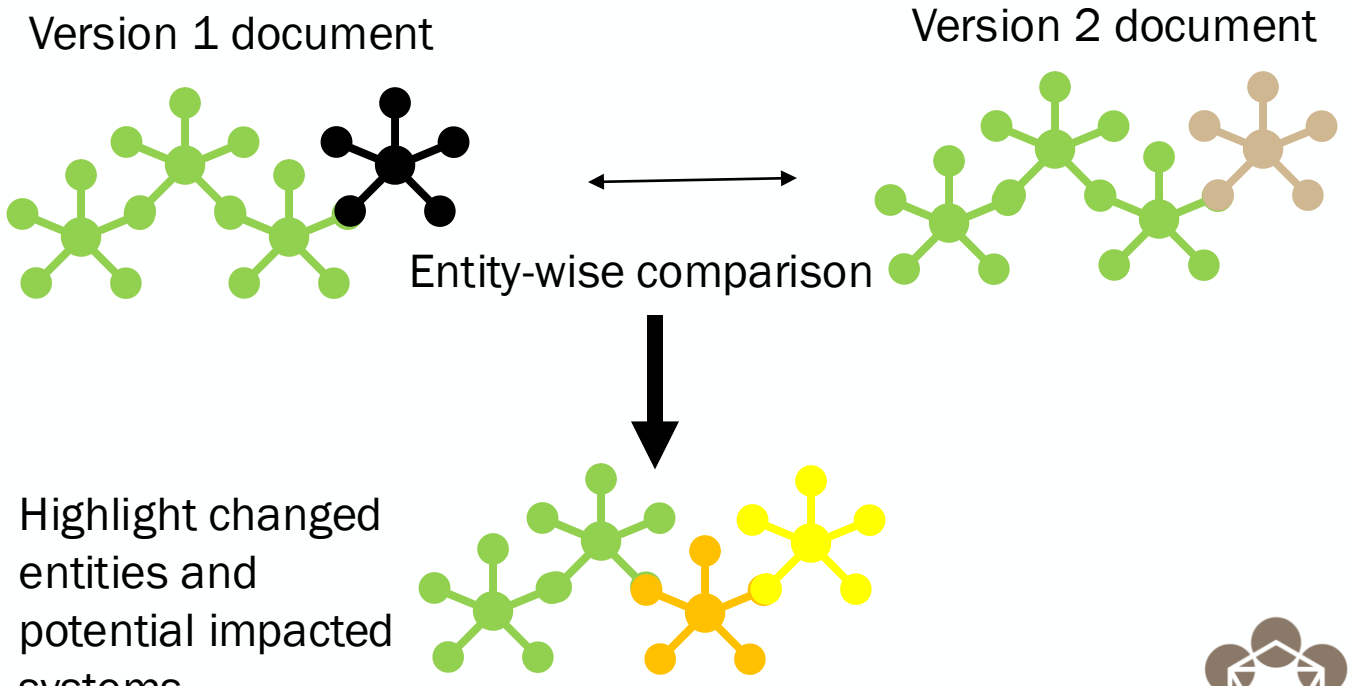


Applications – Querying & Dynamic Insights

Leveraging power of AI and knowledge graph for system integration

- **Multi-perspective querying**: users choose ontology lens for retrieving information
- **Temporal reasoning/Impact analysis**: version control for evolving SoS documents
- **Contradiction detection**: flags inconsistencies, links back to source docs
- **Requirement traceability:** Integration with MBSE Workflows



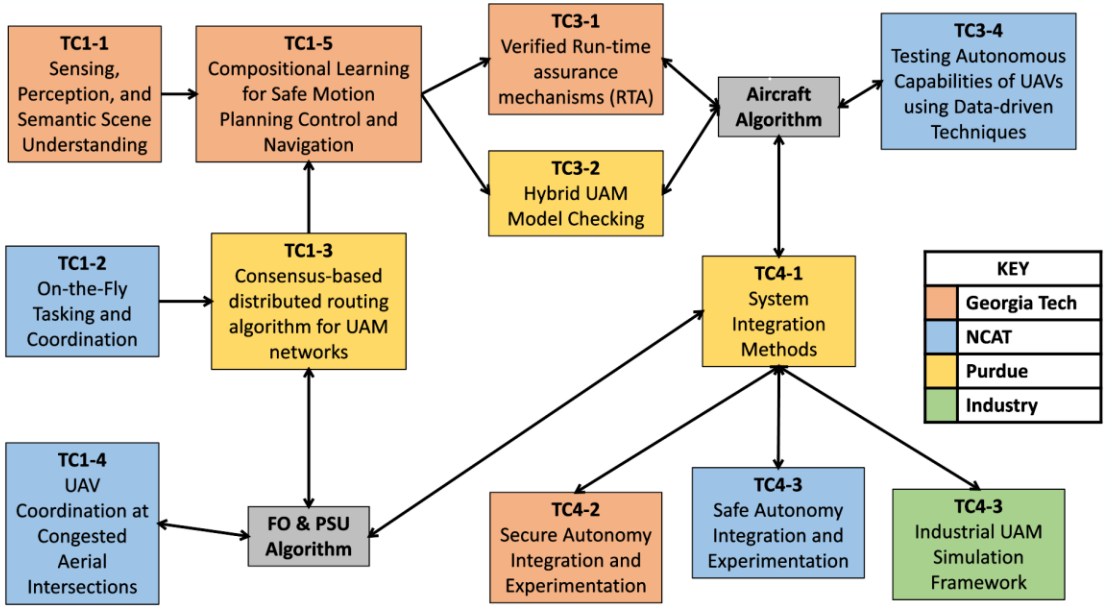


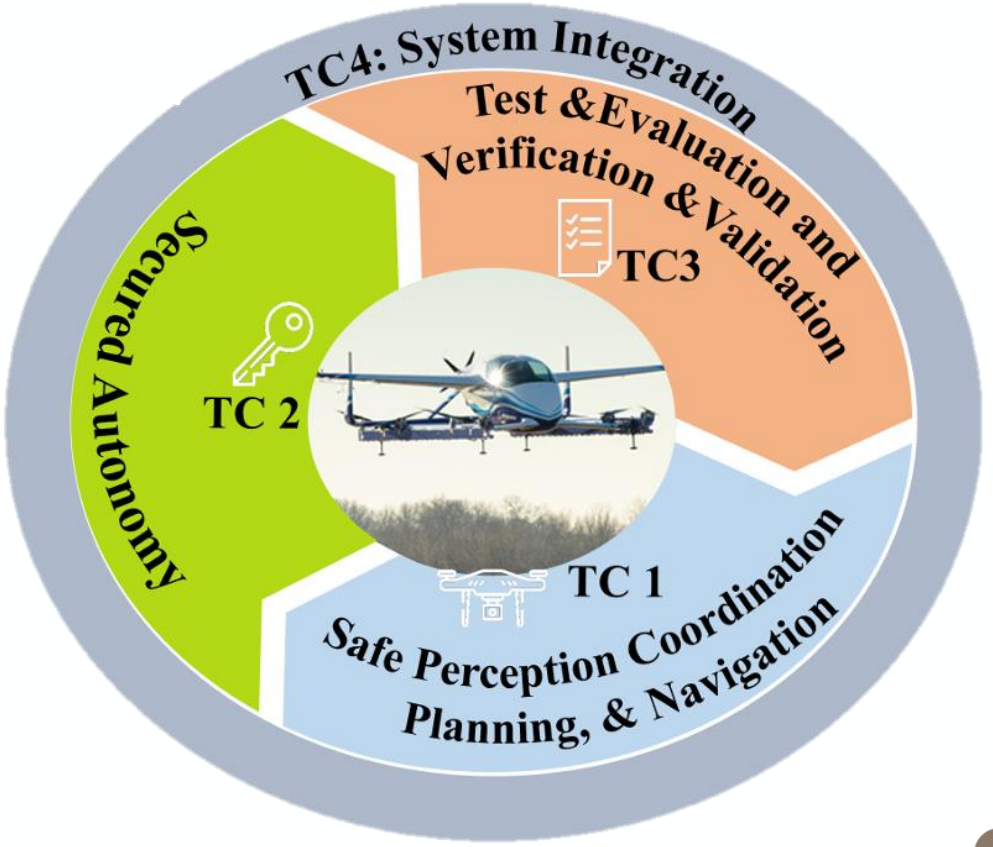
Example and Result

NASA S2A2 (Secure & Safe Assured Autonomy)

Test bed for onto-graph

- Onto-graph is applied to addressed critical integration challenges:
  - Interdisciplinary collaboration
  - Aligning terminology across stakeholder
  - Document version control and impact analysis
- **Enabled traceable dynamic knowledge integration**

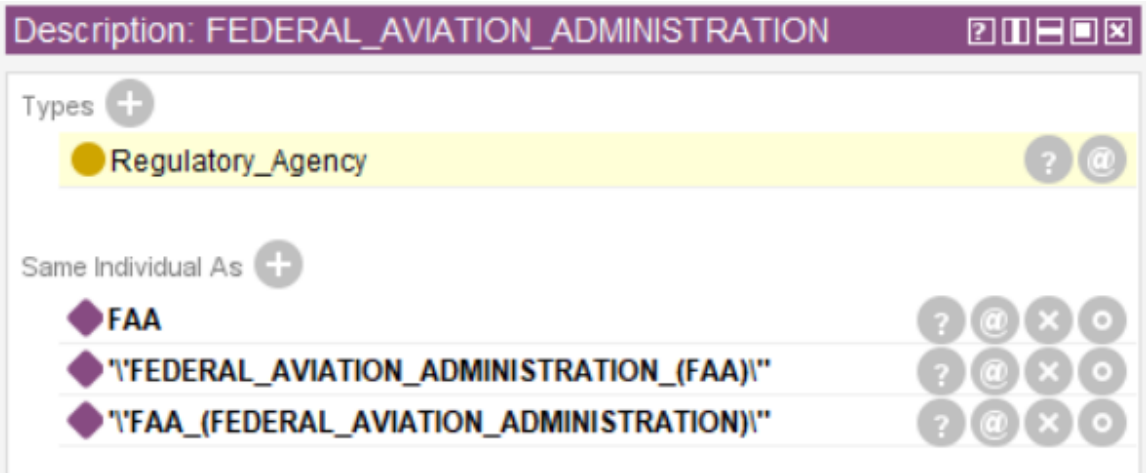


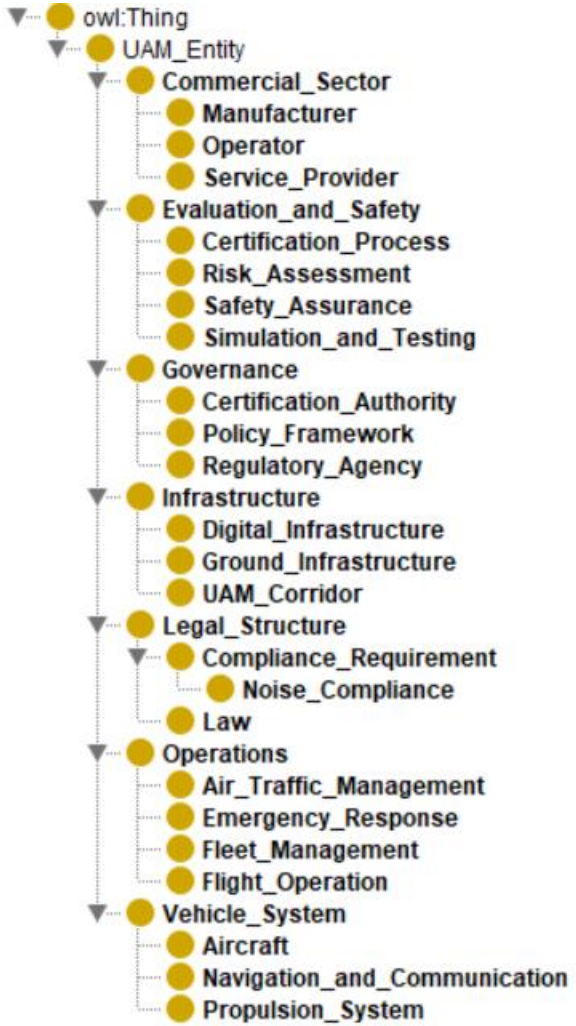


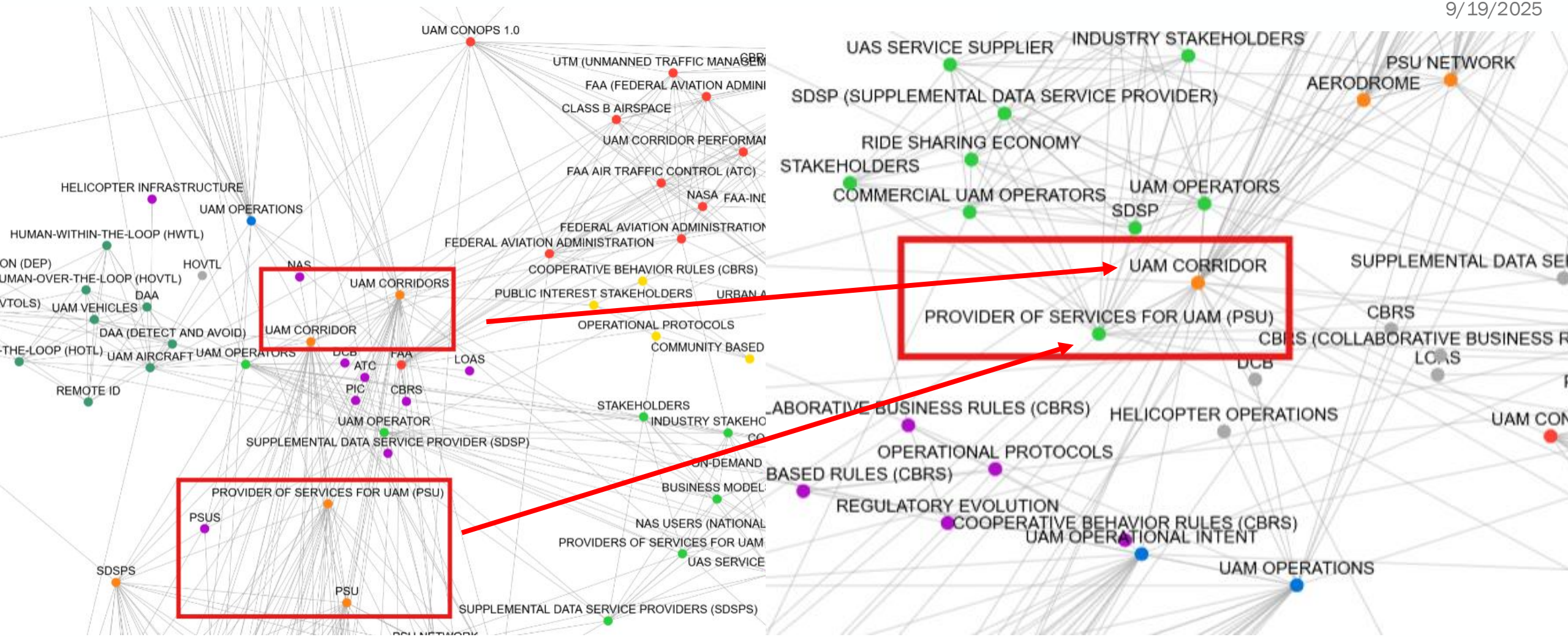
Result: Ontology-Guided Indexing Output

Merging Entities and Aligning Terminology for SoS Integration

- Input: UAM ConOps v1.0 (27 pages)
- Extracted: **122 nodes & 152 relationships** before ontology mapping.
- After ontology mapping & merging : **104 nodes & 127 relationships.**
- Ontology mapping aligns terms to top-level categories
- Identical entities are detected and defined in Ontology
- Produces a **semantically aligned, reduced-complexity knowledge graph**.






UAM CONOPS 1.0
UTM (UNMANNED TRAFFIC MANAGEM
FAA (FEDERAL AVIATION ADMINI
CLASS B AIRSPACE
UAM CORRIDOR PERFORMAI
FAA AIR TRAFFIC CONTROL (ATC)
NASA
FAA-IND
HELICOPTER INFRASTRUCTURE
UAM OPERATIONS
HUMAN-WITHIN-THE-LOOP (HWTL)
FEDERAL AVIATION ADMINISTRATION
FEDERAL AVIATION ADMINISTRATION
COOPERATIVE BEHAVIOR RULES (CBRS)
PUBLIC INTEREST STAKEHOLDERS
URBAN A
ON (DEP)
HOVTL
NAS
UAM CORRIDORS
UMAN-OVER-THE-LOOP (HOVTL)
DAA
VTOLS)
UAM VEHICLES
OPERATIONAL PROTOCOLS
DAA (DETECT AND AVOID)
UAM CORRIDOR
COMMUNITY BASED
-THE-LOOP (HOTL)
UAM AIRCRAFT
UAM OPERATORS
DCB
FAA
ATC
LOAS
REMOTE ID
PIC
CBRS
STAKEHOLDERS
INDUSTRY STAKEHO
UAM OPERATOR
SUPPLEMENTAL DATA SERVICE PROVIDER (SDSP)
ON-DEMAND
BUSINESS MODEL
PROVIDER OF SERVICES FOR UAM (PSU)
PSUS
NAS USERS (NATIONAL
PROVIDERS OF SERVICES FOR UAM
UAS SERVICE
SDSPS
PSU
SUPPLEMENTAL DATA SERVICE PROVIDERS (SDSPS)
UAS SERVICE SUPPLIER
INDUSTRY STAKEHOLDERS
PSU NETWORK
AERODROME
SDSP (SUPPLEMENTAL DATA SERVICE PROVIDER)
RIDE SHARING ECONOMY
STAKEHOLDERS
COMMERCIAL UAM OPERATORS
UAM OPERATORS
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UAM CORRIDOR
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LABORATIVE BUSINESS RULES (CBRS)
HELICOPTER OPERATIONS
UAM CON
OPERATIONAL PROTOCOLS
BASED RULES (CBRS)
REGULATORY EVOLUTION
COOPERATIVE BEHAVIOR RULES (CBRS)
UAM OPERATIONAL INTENT
UAM OPERATIONS

Result : Semi-supervised clustering

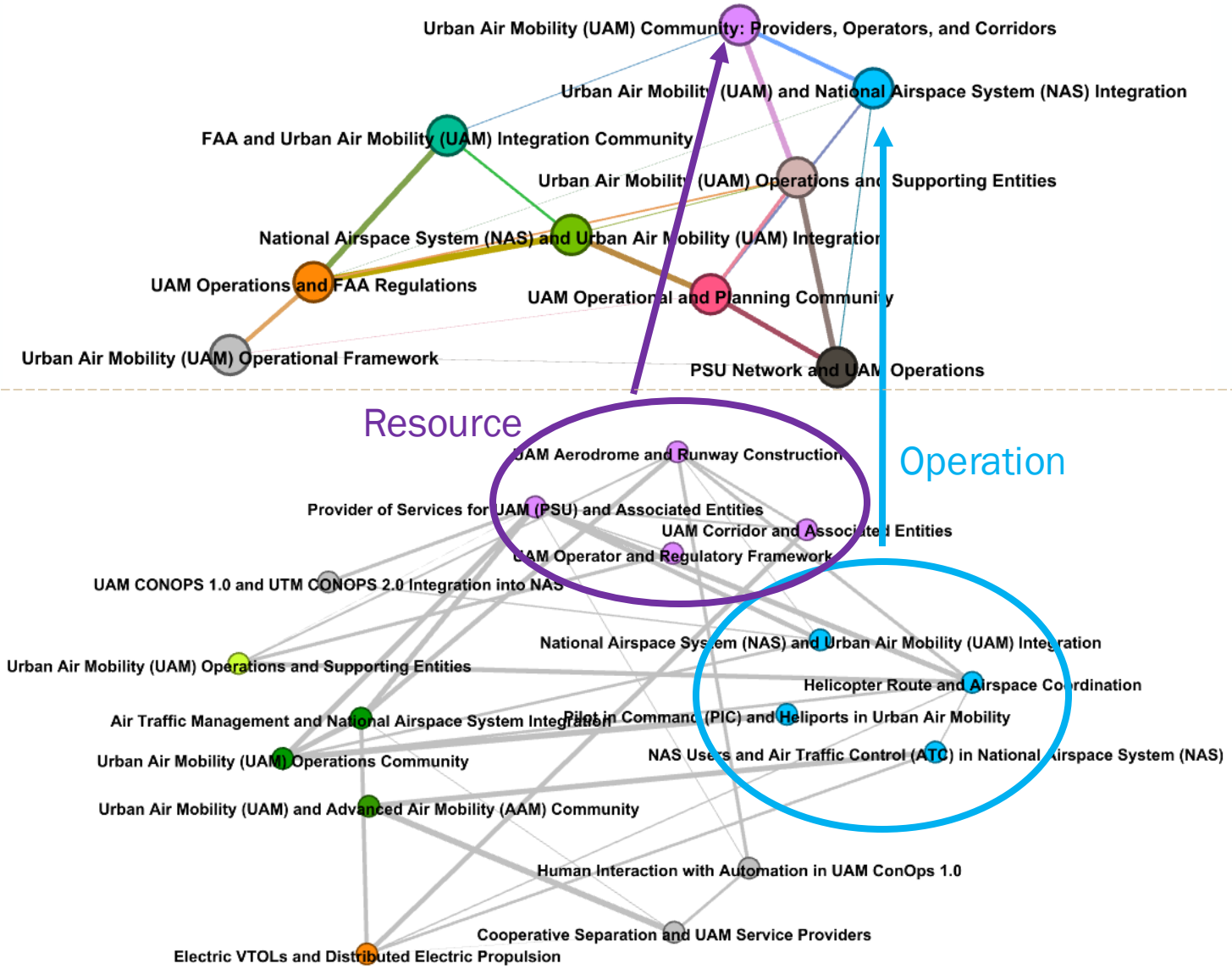
ROPE-guided clustering and hierarchical abstraction

- Entities assigned to ROPE categories (Resource, Operation, Policy, Economy) + ontology classes as clustering seeds.
- Edge weights adjusted: stronger links for nodes sharing ontology/ROPE labels; extra DoF lets user tune emphasis.
- Edge weight set to 1 in this case – clusters will tend to form within the ROPE category

Hierarchical abstraction

Level 2 clusters

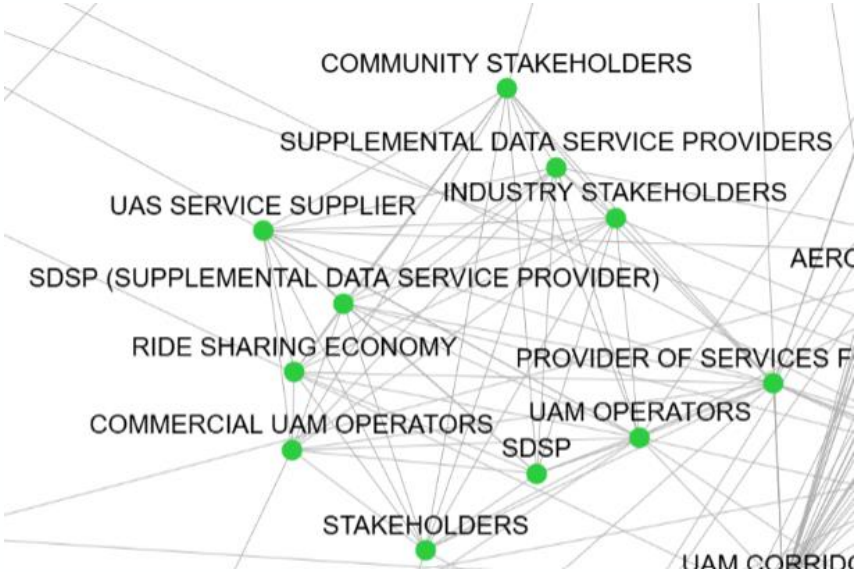
Level 1 clusters



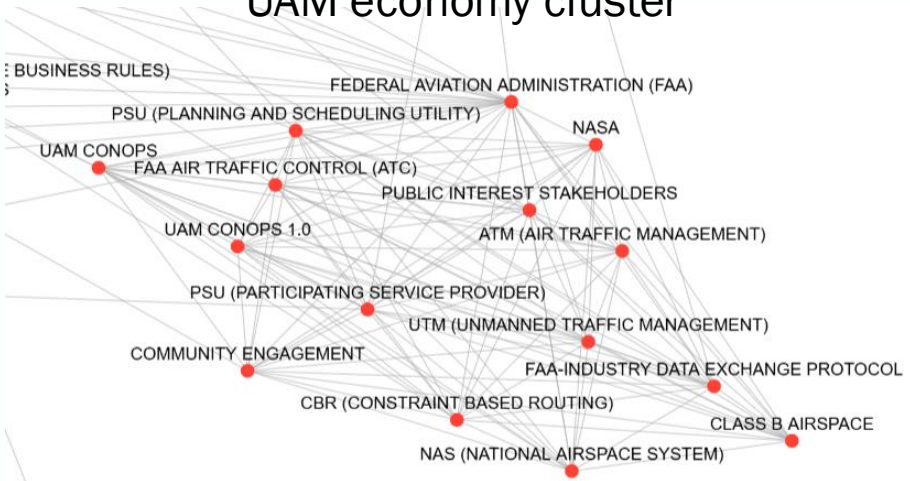
Result : Multi-perspective Querying and Visualization

Ontology Perspectives Enable Stakeholder-Specific Insights

- Users can choose which **ontology perspective** (e.g., ROPE categories) to apply during querying.
- Example query: *"What is FAA's role in UAM development?"*
- **Commercial perspective** → highlights FAA's role in certification, industry standards.
- **Operational perspective** → highlights FAA's role in air traffic management, flight operations.
- Visualization tool:
  - Retrieves **relevant entities and relations** used to construct the answer.
  - Highlights them directly on the graph for transparency.
- Demonstrates how **the same SoS knowledge base** supports multiple stakeholder viewpoints.



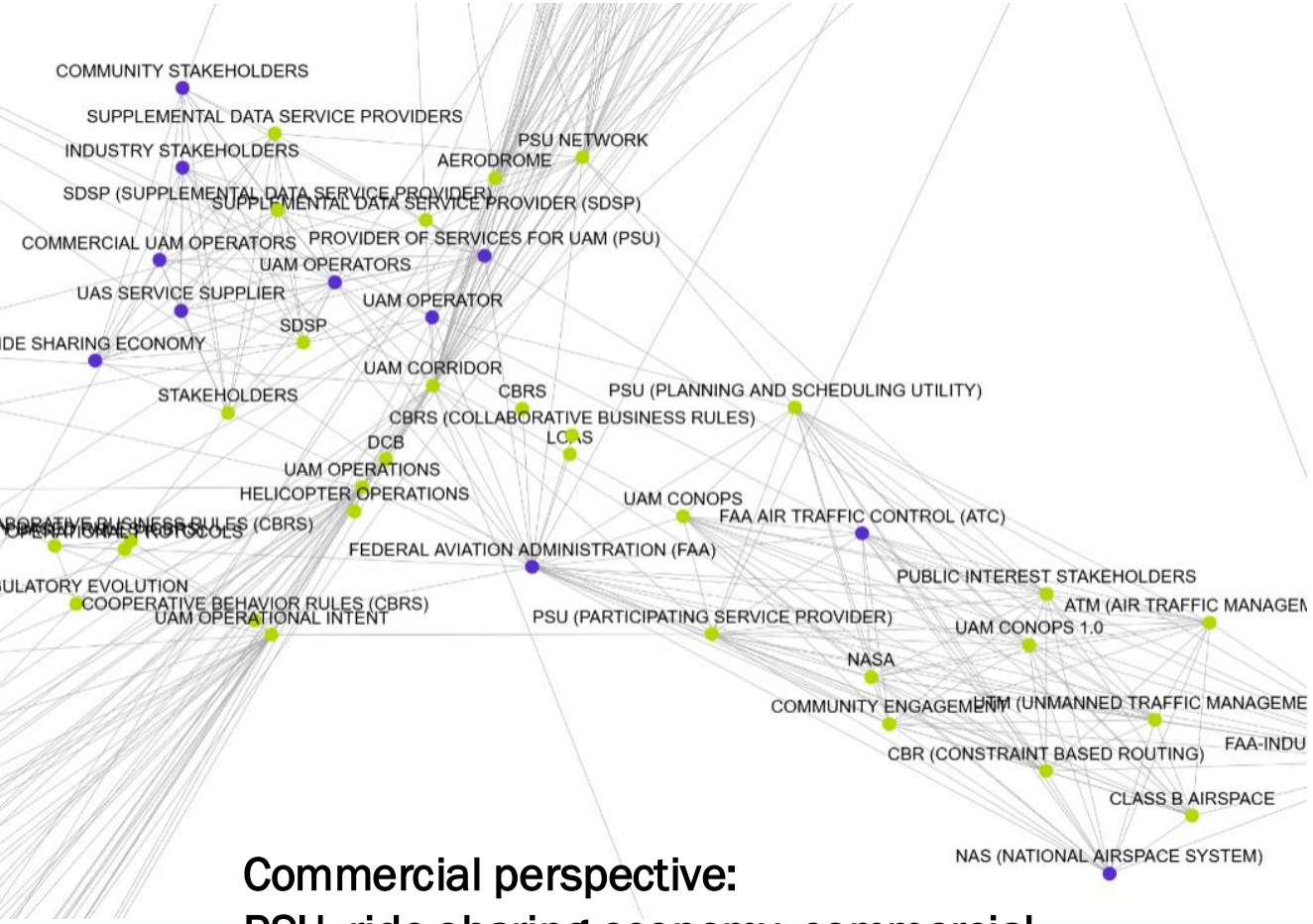
UAM economy cluster



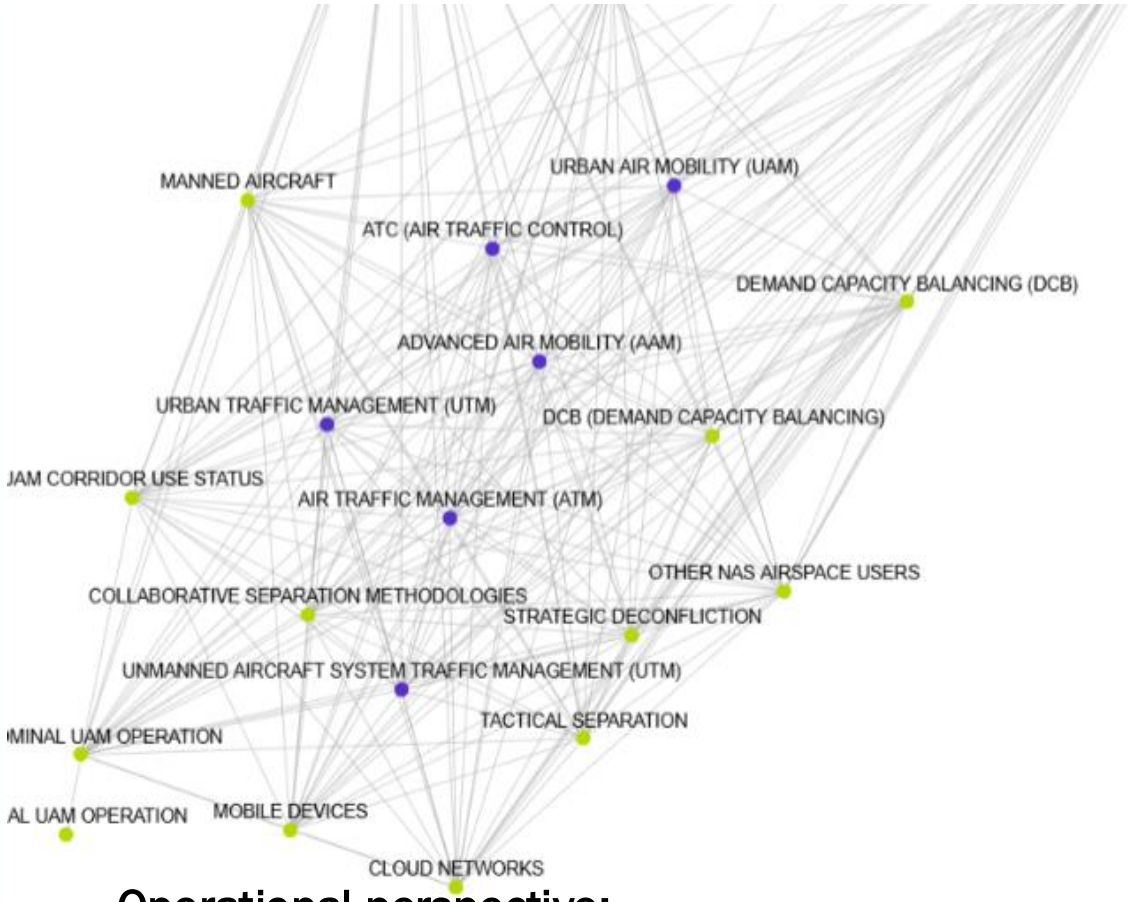
UAM governor cluster

Retrieved entities from different perspective

What is FAA's role in UAM development?"



Commercial perspective:
PSU, ride sharing economy, commercial UAM operators, community stakeholders…

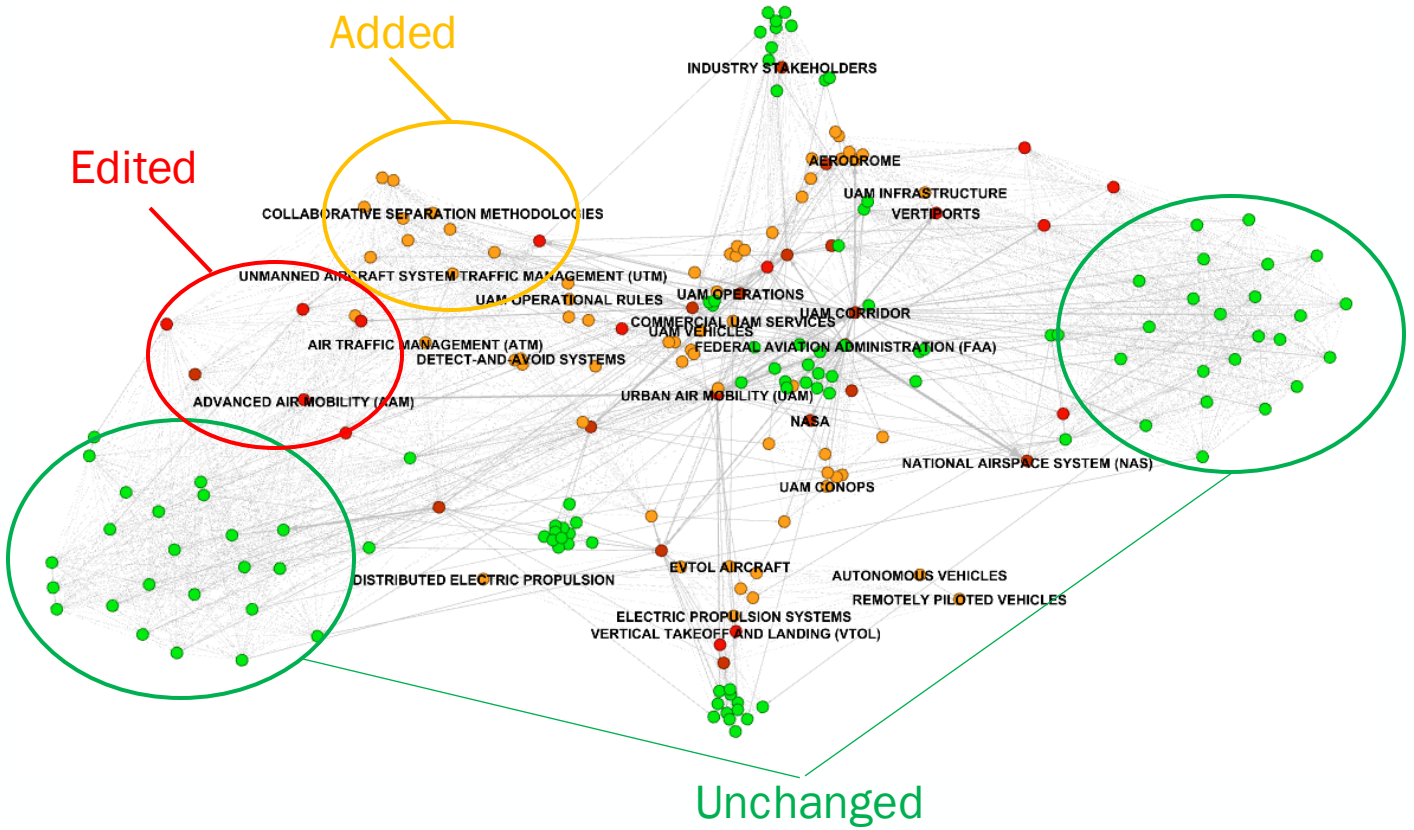


Operational perspective:
ATC, UAM corridor, Urban traffic management, Advance air mobility…

Results – Temporal Reasoning & Impact Analysis

Tracking Evolution and Assessing System-Level Impacts

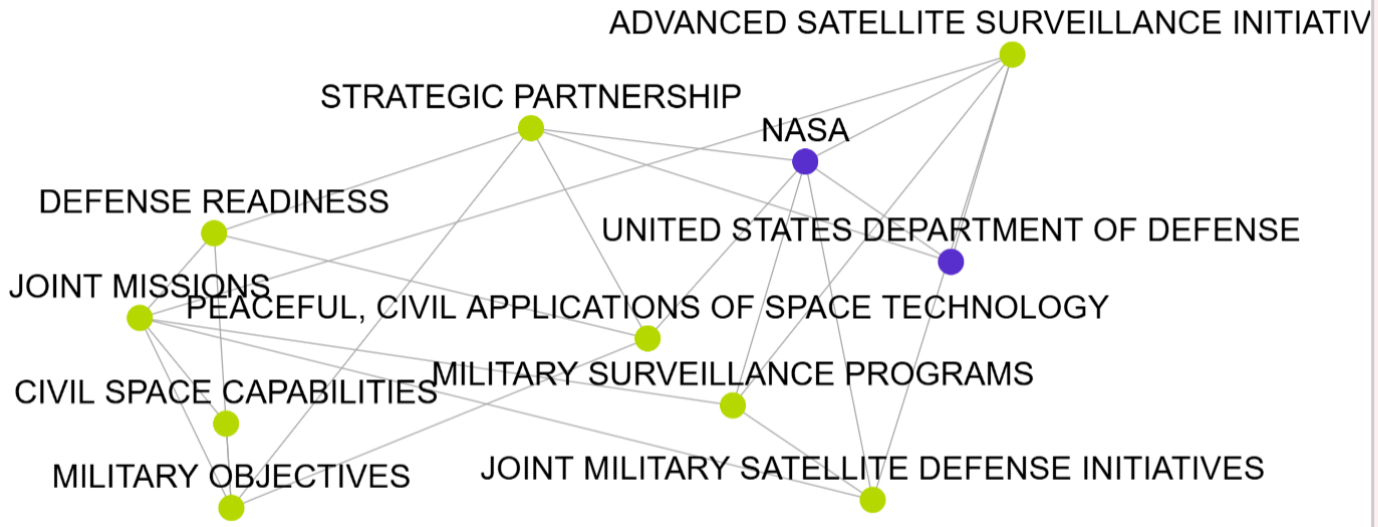
- UAM ConOp v1.0 and 2.0 are input to the system
- Different version of document are compared in entity level based on embedding and semantic meaning
- Identifying **which subsystems are impacted** by changes (impact analysis)
- Labeled entities can be used to construct query related to document version control
- Supports **adaptability in dynamic SoS environments**, where terminology and requirements evolve rapidly.

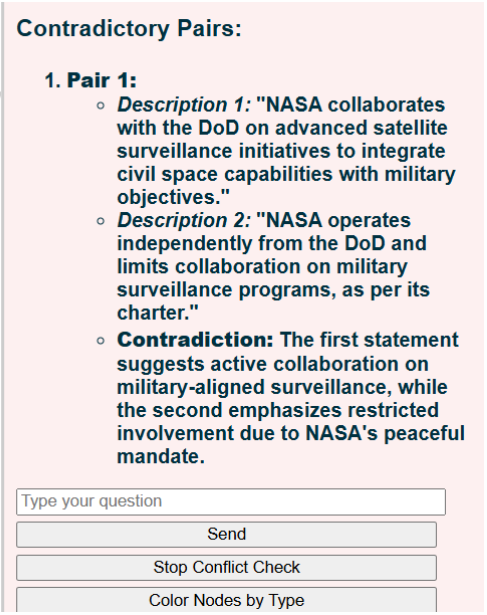


Example: Contradiction detection

Flagging Inconsistencies Across Knowledge Sources

- Relations between same entity pairs merged → LLM detects conflict or agreement.
- Contradictory statements flagged and linked back to source documents.
- Demo dataset (constructed for illustration):
  - “NASA collaborates with DoD on satellite surveillance” vs.
  - “NASA operates independently from DoD, prohibits joint military programs”



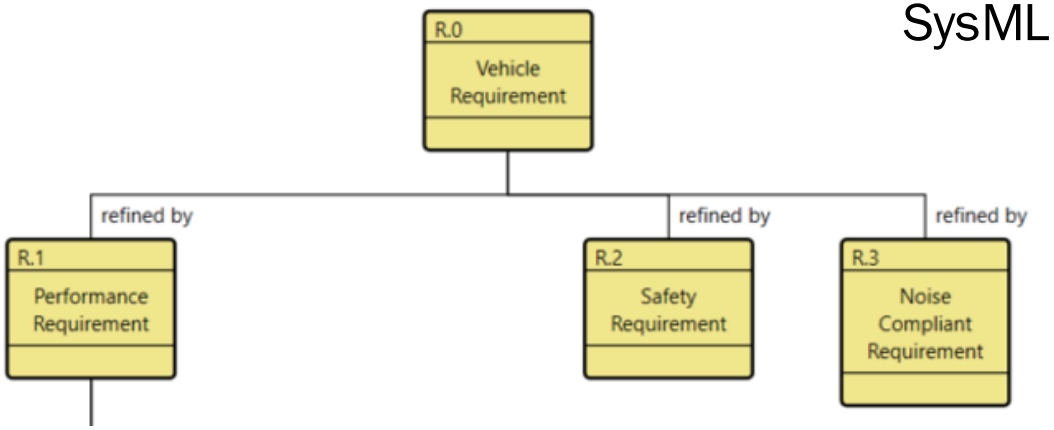


Example: MBSE Model Interaction

Bridging Knowledge Graphs with Model-Based Systems Engineering

- MBSE tools (like SysML) define **structured models** for system requirements and architecture
- Traditional MBSE struggles to ingest **unstructured documents**
- Onto-graph:
  - Maps SysML elements to knowledge graph nodes
  - Links requirements to supporting evidence and documents
  - Provides traceability and **context-aware** answers from unstructured sources
- Result: More adaptive, explainable, and dynamic MBSE frameworks

SysML



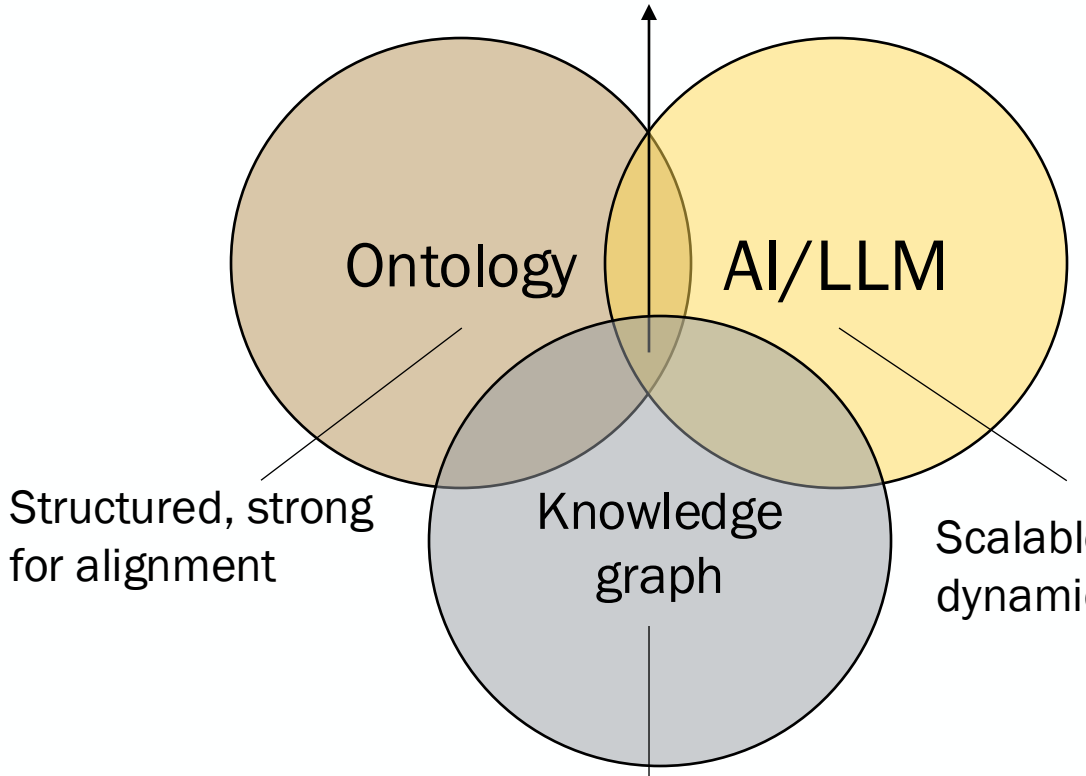
Onto-graph

Revisiting Problem statement

How Onto-Graph Addresses the Core Challenges

- Inefficient collaborations caused by inconsistent vocabulary ->**Mapping entity to ontology class**
- Difficulty integrating unstructured data ->**Use AI to process unstructured data**
- Managing Complexity at Scale ->**Multi-level abstraction by semi-supervised clustering**
- Keeping Models Up-to-Date with Change ->**Entity-wise comparison and impact analysis**
- Conflict and Discrepancy Detection in early stage of design ->**Conflict detection in KGs**

Onto-graph: A hybrid framework combining ontology and LLM to assist SoS engineering



Future work and potential impact

Advancing Onto-Graph Toward Broader SE Applications

Remaining work

- Propose **evaluation criteria** and implement it for ontology mapping(semantic coverage, alignment accuracy)
- Define **metrics for clustering** (modularity, coherence, interpretability)
- Extend contradiction detection from entity/edge level → **higher-level clusters and subsystems**
- Incorporate **multimodal sources** (figures, diagrams, tables)

Potential impact

- Provides **semantic interoperability** across heterogeneous SoS stakeholders
- Enables scalable**, interpretable AI** for engineering contexts assistant
- Supports **dynamic system evolution** via temporal and version-aware reasoning

Thanks!

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