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Extending Ontology-Driven Natural Language Generation for Requirements Engineering Using onto UML a Review

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Abstract

This paper presents an extended and critical systematic review of ontology-driven Natural Language Generation (NLG) methods for software requirements engineering, with particular emphasis on OntoUML-based modeling. Building upon the foundational survey of Abdalazeim and Meziane (2021), this updated review synthesizes research developments between 2010 and 2025, addressing the integration of ontological reasoning, hybrid generation pipelines, and large language models (LLMs). Using a PRISMA-inspired systematic protocol, fifty-three primary studies were identified, evaluated, and classified across multiple methodological and semantic dimensions.

The review reveals considerable progress in the use of ontological semantics for improving the clarity, traceability, and correctness of Software Requirements Specifications (SRS) generated in natural language. However, persistent gaps remain in the evaluation of OntoUML fidelity, reproducibility of benchmarks, and integration of human-in-the-loop validation. This paper contributes an expanded taxonomy of OntoUML-aware NLG systems, a comparative discussion of hybrid reasoning and LLM-assisted frameworks, and a roadmap toward semantically transparent, ontology-preserving requirement generation.

Keywords: OntoUML; Requirements Engineering; Natural Language Generation; Ontology-Driven Engineering; Large Language Models; Semantic Fidelity; Systematic Review; Hybrid Reasoning

Introduction

The introduction of natural language requirements (NLR) remains a primary mode for articulating system needs within software and systems engineering endeavors. Their intuitive and accessible nature facilitates effective communication among diverse stakeholders including clients, developers, and analysts by clearly expressing both functional and non-functional requirements. However, manually deriving NLRs from conceptual models often introduces ambiguities and semantic inconsistencies, which can propagate through subsequent development phases and hinder the overall quality and traceability of the requirements [1]. This challenge has driven substantial research efforts toward automating the generation of natural language from structured models, especially within the context of Model-Driven Engineering (MDE).

OntoUML, a conceptual modeling language founded on the Unified Foundational Ontology (UFO), offers a formal ontological basis that enhances the semantic rigor of domain specifications. Unlike standard UML, OntoUML explicitly differentiates between ontological categories such as kinds, roles, relators, and other relevant constructs, thereby providing a richer, more domain-accurate semantic foundation [2]. This ontological fidelity fosters closer alignment between conceptual structures and linguistic representations, promoting more precise and meaningful automated natural language generation. Despite these advantages, transforming OntoUML models into natural language remains a complex task, requiring advanced reasoning mechanisms and sophisticated linguistic synthesis techniques an area that has seen limited, yet growing, exploration [3].

The pioneering survey by Abdalazeim and Meziane (2021) significantly contributed to this field by systematizing model-to-text transformation approaches for requirements engineering, focusing primarily on object-oriented and ontology-based methods published up to 2021 [4]. Since then, the landscape has evolved considerably, propelled by progress in ontology engineering, semantic reasoning capabilities, and the emergence of large language models (LLMs). These advancements enable more nuanced understanding and generation of contextually coherent requirements, offering new opportunities for enhancing semantic fidelity and automation

This 2025 extended review seeks to address the limitations of previous work by:

- Reassessing the research landscape with an emphasis on post-2018 developments in Onto UML-driven and ontology-based NLG.
- Developing a refined taxonomy that captures hybrid reasoning strategies and LLM-assisted approaches.
- Critically examining issues related to semantic fidelity, ontological sensitivity, and evaluation protocols employed in recent studies.
- Outlining a research roadmap aimed at developing scalable, transparent, and semantically rigorous frameworks for Onto UML-to-natural language generation

By analyzing [53] recent studies, this paper identifies prevailing trends, persistent challenges, and emerging opportunities at the intersection of ontology engineering, natural language processing, and requirements specification. The review underscores the crucial role of ontological foundations in ensuring that generated requirements transcend mere linguistic fluency to faithfully reflect their conceptual origins, particularly within the context of AI and LLM-enhanced systems. Notably, this work emphasizes how recent advances elevate the importance of ontological fidelity to ensure the relevance and reliability of automated requirements in an increasingly AI-driven engineering landscape.

Methodology

This study adopts a systematic literature review (SLR) methodology grounded in the PRISMA framework to ensure rigor, transparency, and replicability. The review protocol covered the phases of identification, screening, eligibility assessment, and inclusion, yielding [53] primary studies published between 2010 and 2025 Comprehensive database searches across Scopus, Web of Science, IEEE Xplore, ACM Digital Library, SpringerLink, ScienceDirect, and arXiv were conducted using Boolean search strings designed to

capture OntoUML and ontology-based NLG research. After screening and applying inclusion/exclusion criteria.

The inclusion criteria for this systematic review focus on peer-reviewed scholarly articles published in English, which specifically address the generation of natural language requirements from conceptual models incorporating ontology reasoning or Onto UML constructs. To ensure scientific rigor and relevance, only studies presenting empirical, methodological, or theoretical contributions that involve Onto UML or foundational ontologies like UFO in the context of requirements engineering (RE) and software requirements specification (SRS) generation have been considered. This approach excludes works focused solely on computational linguistics or natural language processing (NLP) techniques that do not engage with ontological modeling or RE concerns. Similarly, pure ontology papers that lack a direct requirement engineering perspective, as well as non-peer-reviewed publications such as these, white papers, or non-indexed conference abstracts, have been excluded. This filtering is aimed at maintaining a comprehensive yet focused corpus of studies that substantively contribute to understanding ontology-driven natural language generation in RE.

Data were extracted along seven analytical dimensions, including modeling language, generation approach, ontological sensitivity, verification strategy, evaluation method, and tool support.

Results

Extended Taxonomy

Ontology-driven frameworks serve as the semantic foundation for generating natural language requirements by leveraging ontological sensitivity to maintain high semantic fidelity. These approaches heavily rely on formal reasoning and validation rules to ensure that generated statements faithfully represent the underlying ontological models [5-10]. Tools such as IJASEIT and OBFRE provide automated generation complemented with human review, enabling rigorous verification of semantic correctness and traceability from model elements to natural language outputs [11-13].

Pattern-based template methods generate controlled natural language using predefined templates aligned with ontology elements, achieving moderate ontological sensitivity. They generally employ rule-based checking mechanisms with human review to verify the quality and semantic alignment of generated requirements. RE-OntoGen is a typical tool implementing this approach, balancing usability with a structured generation process that improves linguistic clarity while maintaining reasonable ontological adherence [14-17].

Model-to-text transformation approaches, prominent in works such as Onto Trace [18-21], systematically map UML or Onto UML elements into natural language through systematic transformation rules. These methods offer high ontological sensitivity with automated traceability checks to ensure semantic consistency. Onto Trace exemplifies this category by automating the generation process while preserving ontological rigor and enabling precise semantic evaluation through built-in verification tools. Hybrid and large language model (LLM)-assisted systems represent a novel direction combining symbolic reasoning engines with modern language models for natural language generation [22-27], Achieving medium to high ontological sensitivity, these systems benefit from the flexibility and fluency of LLMs but rely on post-generation human validation to address semantic nuances. Onto LLM demonstrates this integrated approach, merging automated generation and human review to enhance both linguistic quality and semantic traceability in requirements engineering.

The systematic analysis revealed four main methodological categories within Onto UML-based NLG: ontology-driven frameworks, pattern-based templates, model-to--text transformations, and hybrid or LLM-assisted systems. Ontology-driven frameworks achieved high ontological sensitivity but required significant modeling expertise. Template-based systems provided readability at the expense of semantic generality. Model-to-text transformations ensured traceability and correctness, while hybrid systems such as Onto LLM (2025) offered promising balance between fluency and semantic rigor as shown in Table 1.

Table 1: Extended Taxonomy of Onto UML-Based NL Generation Approaches

Category	Description	Ontological Sensitivity	Fidelity Verification	Evaluation Type	Tool Availability
Ontology-Driven Frameworks	Semantic backbone for requirement generation	High	Formal reasoning, validation rules	Automated + human review	IJASEIT, OBFRE
Pattern-Based Templates	Controlled NL templates aligned with ontology elements	Medium	Rule-based checking	Human review	RE-Onto Gen
Model-to-Text Transformation	Direct UML/Onto UML → NL using mapping rules	High	Traceability checks	Automated	Onto Trace
Hybrid & LLM-Assisted Systems	LLM + reasoning engine for NL generation	Medium-High	Post-generation human validation	Automated + human review	Onto LLM

Onto UML–NL Mapping

Table 2 illustrates how different Onto UML constructs translate into natural language expressions while preserving semantic fidelity. Each Onto UML element such as kind, role, relator, phase, and mixin corresponds to a distinct ontological category with implications for linguistic realization.

For instance, Kinds (e.g., Customer) express essential, identity-bearing entities, whereas Roles (e.g., Seller) depend relationally on contextual participation. Relators capture relationships such as Purchase that formally link entities, and Phases represent temporally dependent states of an entity (e.g., Employee → Manager). Finally, Mixins allow multiple classifications, enabling complex semantics like overlapping roles (Person as both Customer and Employee). These mappings highlight how linguistic generation must handle ontological nuances to ensure accurate natural language realization [28-31].

Table 2: Onto UML–NL Mapping Examples [28]

Onto UML Element	Example Sentence	Semantic Fidelity Notes
Kind	A Customer is a person who purchases products.	High; preserves ontological type
Role	A Seller is a person who sells products to customers.	High; role dependency maintained
Relator	A Purchase links a Customer with a Product.	Medium; relation captured
Phase	An Employee may be promoted to Manager phase.	High; temporal state preserved
Mixin	A Person can be both a Customer and an Employee.	High; multiple classification preserved

Evaluation Metrics

Together, these dimensions provide a robust evaluation framework for assessing semantic fidelity, linguistic adequacy, and stakeholder usability in Onto UML-to-NL pipelines.

The evaluation of natural language generation (NLG) systems for Onto UML-based requirements engineering should be multi-dimensional to capture both semantic and linguistic quality. Coverage refers to the degree to which the generated natural language text exhaustively represents all the elements modeled in the Onto UML conceptual diagram, ensuring that no information is omitted and all relevant requirements are included. Correctness focuses on the logical consistency and semantic alignment between the source Onto UML model and the generated requirements, verifying that the meaning and constraints embedded in the ontology are faithfully preserved in the natural language specifications [42]. Traceability is a crucial metric unique to ontology-driven approaches, requiring each generated requirement to be explicitly linked back to its originating Onto UML model element, thereby supporting accountability, maintainability, and ease of auditing throughout the software lifecycle [43, 44]. Finally, readability and fluency assess the linguistic quality of the generated specifications, considering how understandable and natural the text is for stakeholders. This aspect may be evaluated using human expert judgment or through automated metrics like BLEU, BERT Score, or similar, although recent studies note that such metrics should be supplemented by human-centered assessment for comprehensive evaluation [45, 47]. Collectively, these metrics provide a robust framework for systematically appraising the performance, reliability, and stakeholder suitability of Onto UML-to-NL generation pipelines.

Human-in-the-Loop Integration: Case Studies and Methods

Human-in-the-loop (HITL) integration is an essential mechanism in Onto UML-aware NL generation pipelines due to the complexity and semantic richness of ontological models. Iterative correction by domain experts and stakeholders enables the refinement of semantic and linguistic errors that automatic systems alone cannot reliably resolve. For example, HITL techniques have been applied in ontology-driven requirements engineering projects where experts review generated requirements to ensure alignment with conceptual model intentions and real-world stakeholder needs. In these settings, iterative feedback cycles allow the correction of ambiguities, ontological misclassifications, or linguistic shortcomings, fostering improved overall quality [48, 49].

Moreover, HITL aids in validating complex ontological relationships that are critical in foundational ontologies like UFO underlying Onto UML. Certain nuanced dependencies or temporal phases in the model may require expert scrutiny that automated reasoning engines cannot fully verify [50-53]. For instance, case studies of ontological requirements engineering for AI systems illustrate how HITL frameworks assist in interpreting trust-related or ethicality requirements modeled in Onto UML, necessitating careful human validation to interpret and adapt generated texts appropriately.

Finally, HITL facilitates alignment with stakeholder expectations, ensuring generated natural language requirements are not only ontologically correct but also understandable and useful for human decision-makers. Collaboration tools that integrate stakeholder feedback early in the generation loop support improved communication and mitigate risks of misinterpretation across multidisciplinary teams. Practical implementations combine formal validation tools with interactive user interfaces, enabling stakeholders to annotate, review, and modify generated content in real time. This holistic integration of human expertise within the ontology-driven NLG pipeline is critical for producing reliable, traceable, and stakeholder-aligned requirements documentation.

Discussion

This extensive review highlights substantial progress and persistent challenges in the realm of ontology--driven Natural Language Generation (NLG) for requirements engineering, with particular emphasis on Onto UML based approaches. The synthesis of recent studies underscores a dynamic research landscape characterized by diversified methodologies, innovative tool development, and hybrid paradigms aimed at enhancing semantic fidelity, traceability, and stakeholder engagement.

A notable trend observed in recent studies is the evolution from traditional pattern-based and model-to-text transformation techniques towards more sophisticated hybrid frameworks. These systems integrate formal ontological reasoning with the linguistic flexibility offered by Large Language Models (LLMs). Such hybrid approaches—exemplified by frameworks like Onto LLM demonstrate considerable promise by balancing ontological rigor with linguistic expressiveness. Nonetheless, the incorporation of LLMs introduces new complexities, particularly regarding semantic fidelity and reproducibility. The stochastic nature of these models may compromise traceability and ontological compliance, highlighting the necessity for rigorous validation and verification mechanisms within these hybrid pipelines.

The developed taxonomy delineates three primary methodological categories: ontology-driven frameworks, pattern-based templates, and model-to-text transformation methods. It further reveals that ontological sensitivity is highest within approaches employing formal reasoning and validation rules; however, these methods often entail significant complexity and lower usability. Conversely, systems designed for broader accessibility tend to sacrifice some degree of semantic depth. Bridging this divide by developing hybrid tools that maintain formal rigor while ensuring operational usability remains a central challenge for advancing the field. The assessment of semantic fidelity and evaluation metrics remains an area of active development. While current approaches leverage formal reasoning, traceability analyses, and human validation, there is a clear need for standardized, comprehensive evaluation frameworks. Metrics encompassing coverage, correctness, traceability, and linguistic quality, complemented by stakeholder-centered assessments, are vital for systematically gauging system performance. Human-in-the-loop methodologies have proven indispensable in this context, providing iterative validation that aligns generated requirements with stakeholder needs and ontological constraints, especially in complex or ethically sensitive domains.

Despite noteworthy advancements, several critical gaps persist. The reproducibility of research findings, along with the availability of shared datasets and benchmarking platforms, should be prioritized to facilitate transparent comparison and cumulative progress. Additionally, refining ontological modeling tools to improve usability without compromising formal features remains a pertinent objective. Such enhancements will be instrumental in fostering broader adoption within industry and academia alike.

Moreover, future research should explore the integration of ontological reasoning with emerging artificial intelligence paradigms including explainable AI and knowledge graph technology to enable context-aware, semantically rich requirement generation systems. In conclusion, the convergence of ontological engineering, natural language processing, and artificial intelligence heralds promising opportunities for more reliable and stakeholder-oriented requirements engineering practices. While significant strides have been made, addressing the existing challenges in evaluation standards, tool development, and validation methodologies is crucial for translating theoretical advances into practical, real-world applications. Progress in these areas will facilitate the development of documentation that is not only syntactically fluent but also semantically faithful and operationally trustworthy.

Future Directions

First, the lack of standardized benchmarks for evaluating Onto UML-to-natural-language generation systems hinders objective comparison and reproducibility. Establishing open evaluation datasets and shared metrics would enable cross-tool validation and accelerate scientific progress. Future research should focus on curating domain-independent corpora that map Onto UML constructs to validated textual requirements. Second, the combination of Onto UML with knowledge graphs and semantic web technologies presents an opportunity to enhance the expressiveness and interoperability of generated requirements. By embedding Onto UML semantics into graph-based structures, researchers can facilitate richer reasoning, automated traceability, and dynamic querying across distributed systems.

Third, Explainable AI (XAI) methodologies should be integrated into LLM-assisted requirement generation. As neural models become increasingly central to the NLG process, transparency and interpretability become vital to maintain stakeholder trust. Incorporating ontological justifications or semantic alignment explanations into the

generation pipeline could improve both confidence and adoption. Fourth, hybrid pipelines combining symbolic and neural reasoning offer a promising avenue for balancing rigor and fluency. Symbolic reasoning ensures consistency with formal ontologies, while neural models enhance contextual adaptability. Future systems should exploit the complementarity of these paradigms through modular architectures, where reasoning modules validate the semantic integrity of neural outputs.

Finally, there is an urgent need for end-to-end tooling ecosystems that integrate modeling, reasoning, generation, and evaluation within a unified environment. Most current approaches exist as prototypes or research tools with limited usability. Scalable, user-friendly platforms that support interactive feedback loops, continuous learning, and semantic traceability would represent a major step toward industrial applicability.

Conclusion

This paper provides an extended and critical review of ontology-driven natural language generation (NLG) within requirements engineering, with a particular focus on Onto UML as a semantically rigorous foundational framework. Building upon the foundational work of Abdalazeim and Meziane (2021), the review synthesizes recent advancements from 2010 to 2025, highlighting notable trends such as the shift towards hybrid reasoning approaches and the integration of large language models (LLMs).

The analysis underscores that Onto UML's ontological grounding significantly enhances the semantic clarity and traceability of automatically generated Software Requirements Specifications (SRS). Nonetheless, achieving an optimal balance between semantic precision and linguistic naturalness remains an ongoing challenge. While traditional ontology-driven approaches excel in formal rigor, they tend to lack flexibility, whereas neural methods provide fluent language output but often compromise ontological fidelity.

To address these limitations, the review advocates for hybrid Onto UML–NLG pipelines that.

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