The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
ASEE
Paper ID #42978

Leveraging Ontologies in Engineering Education: Top-Down and Bottom-Up Approaches

Waterloo Tsutsui, Purdue University

Dr. Waterloo Tsutsui is a Senior Research Associate in the School of Aeronautics and Astronautics at Purdue University, IN. Tsutsui received his Ph.D. in Aeronautics and Astronautics from Purdue University in 2017. Before Purdue, Tsutsui practiced engineering in the automotive industry for more than ten years, with the last position involving the research and development of lithium-ion battery cells for electric vehicles. Tsutsui's research interests are systems engineering, structures and materials, and the scholarship of teaching and learning. Tsutsui is the recipient of the 2023 Engineering Education Excellence Award from the National Society of Professional Engineers (NSPE).

Mr. Vladimir Zeltsman, Purdue University

Vladimir Zeltsman is a graduate student and research assistant at Purdue University. He is currently pursuing his Master's of Science in Aeronautical and Astronautical Engineering. He received his Bachelor of Science in Aeronautical and Astronautical Engineering from Purdue University in 2022. His work specializes in Systems Engineering.

Tyler Scott Adams, Purdue University

Tyler Adams is a Graduate Research Assistant in the School of Aeronautics and Astronautics at Purdue University, IN. Adams is currently pursuing his Master's of Science in Aeronautical and Astronautical Engineering and expects to receive this degree in 2024. Before Purdue, Adams received his Bachelor's of Science in Mechanical Engineering from Brigham Young University in 2022. His research interests include aerospace systems engineering, aerospace design, and computational aerodynamics.

Dr. Jitesh H. Panchal, Purdue University

Dr. Jitesh H. Panchal is a Professor and Associate Head of Mechanical Engineering at Purdue University. He received his BTech (2000) from the Indian Institute of Technology (IIT) Guwahati, and MS (2003) and PhD (2005) in Mechanical Engineering from Georgia Institute of Technology. Dr. Panchal's research interests are in (1) design at the interface of social and physical phenomena, (2) computational methods and tools for digital engineering, and (3) secure design and manufacturing. He is a recipient of CAREER award from the National Science Foundation (NSF); Young Engineer Award, Guest Associate Editor Award, and three best paper awards from ASME. He has served on the editorial board of international journals including ASME Journal of Mechanical Design, ASME Journal of Computing and Information Science in Engineering.

Daniel Delaurentis, Purdue University

Dr. Daniel DeLaurentis is Vice President for Discovery Park District (DPD) Institutes and the Bruce Reese professor of Aeronautics & Astronautics at Purdue University. He directs the Center for Integrated Systems in Aerospace (CISA) researching modeling, design optimization and system engineering methods for aerospace systems and systems-of-systems, including urban and regional Advanced Aerial Mobility and hypersonic systems. He is a Senior Research Fellow at the Krach Institute for Tech Diplomacy at Purdue. DeLaurentis served as Chief Scientist of the U.S. DoD's Systems Engineering Research Center (SERC) UARC from 2019-2023. He is an elected FELLOW of the American Institute of Aeronautics & Astronautics (AIAA) and the International Council on Systems Engineering (INCOSE).

Leveraging Ontologies in Engineering Education: Top-down and Bottom-up Approaches

Abstract

Engineering education is an ever-evolving field that covers a wide range of interconnected disciplines; therefore, educators and students must navigate the body of knowledge efficiently. Given this complexity, this research investigates potential applications of ontologies to enhance aerospace engineering education. The paper will first explore the advantages of incorporating ontologies in engineering education. From this perspective, ontologies serve as a framework that systematically organizes information to create an enhanced educational environment. Then, the paper proposes top-down and bottom-up approaches to ontology integrations in engineering education, where the former enables instructors to provide students with a framework that lays the groundwork for a better understanding of fundamental concepts. In contrast, the latter empowers students to offer context to instructors while contributing detailed insights into subject matters. Lastly, this paper illustrates use cases utilizing the top-down and bottom-up approaches, showcasing the potential use of ontology framework in aerospace engineering education.

1. Introduction

The saying, "The whole is greater than the sum of its parts," often attributed to Aristotle, reflects an understanding of interconnected systems. It suggests that a system as a whole exhibits characteristics and behaviors that go beyond what can be observed by looking at its components, thereby emphasizing the importance of relationships and interactions within the system [1]. In engineering, especially in engineering design, this holistic perspective (i.e., "wholistic" view) holds value because the process involves multiple disciplines that require expertise from these fields to solve complex problems as a team. Even within smaller engineering units, inherent multifunctionality demands a multidisciplinary approach. For example, consider a battery pack for an electric vehicle, which not only serves as an electrochemical energy storage device for propulsion, requiring insights from chemistry but also functions as a kinetic energy absorption device to mitigate the risk of occupant injury during vehicular collisions, necessitating knowledge of impact mechanics [2], [3], [4], [5]. Therefore, to navigate this multidisciplinary approach effectively, students must understand the taxonomy [6] and lexicon [7] associated with their respective engineering fields, ensuring clarity, reducing confusion, and enabling problem identification and resolution. Ultimately, ontology empowers this framework by providing a structured understanding of the categories and relationships within engineering disciplines.

2. Background and Literature Review

2.1 System-of-Systems Engineering Inspired Ontology

The term "ontology" originates from philosophy, specifically within the branch that describes the nature and structure of "reality" [8]. The Oxford English Dictionary [9] defines ontology as "The science or study of being; that branch of metaphysics concerned with the nature or essence of being or existence." As artificial intelligence (AI) has gained traction in recent history, ontologies also gained traction. Gruber (1993), an AI researcher, succinctly defined ontology as "an explicit specification of a conceptualization" [10]. In a system-of-systems (SoS) domain, researchers use ontologies to represent the outcome and the resulting SoS design spaces with involved entities, hierarchies in the SoS space, and their relationships [11]. DeLaurentis et al. (2022) stated, "Ontology is a set of logical relations between elements in a domain and supports logical reasoning within the system" [1]. Borst (1999) and Guarino et al. (2009) further refined the definition by characterizing ontology as "the formal specification of a shared conceptualization" [8], [12].

In examining the SoS framework proposed by Maier [13], we find a structured approach for capturing requirements in SoS design. Maier's work sets the stage for the ontology application as incorporating ontologies into the structured approach can significantly enhance semantic consistency (i.e., a consistent interpretation of data) and interoperability (i.e., an ability of different systems to communicate with each other) among the diverse systems that constitute the SoS. The importance of ontology becomes evident when considering knowledge sharing, utilization, and reuse [14], [15], [16]. Osmundson (2006) reported that the application of ontological engineering, a field to study the methods for building ontologies, has effectively addressed information interoperability requirements for SoS in diverse application domains [17].

A distinctive strength of ontologies lies in their ability to construct, describe, and visualize the entire SoS at varying levels of depth and fidelity [18]. From the viewpoint of SoS engineering, utilizing ontologies proves instrumental in enhancing visualization and comprehension at different systems levels and their interconnections. For instance, the SoS approach may employ ontologies to represent the hierarchy levels visually. To this end, DeLaurentis (2005) used the alpha, beta, and gamma levels to describe the hierarchy levels of SoS [19]. Additionally, the virtual labs, previously reported to enhance aerospace structural education [20], [21], could be leveraged alongside SoS-inspired approaches. To this end, these virtual labs could serve as tangible reinforcement for the SoS-inspired ontology, fostering better comprehension, semantic consistency, and interoperability in engineering education. Integrating game-based learning and SoS-inspired ontology into virtual labs could amplify student understanding of the subject matter.

2.2 Ontology in Collaborative Environment

Within a collaborative environment, ontologies are essential in ensuring a streamlined process that fosters alignment and seamless data sharing among diverse contributors [22]. This alignment encompasses shared terminology researchers employ across disciplines [23]. The overarching objective is to standardize processes, creating a uniform dataset beyond disciplinary boundaries. This standardization mitigates risks associated with collaboration. For instance, avoiding inconsistencies in variable naming and code formatting in collaborative coding activities becomes paramount to preventing inefficiencies and misunderstandings [24]. In addition, the effort to streamline extends beyond coding scenarios and addresses the primary challenge of interpreting diverse terminology. Ontologies are pivotal in establishing a standardized dataset, vocabulary, and methodology, ensuring consistent meaning for all stakeholders [25].

Facilitating quick and comprehensible data passing through among team members ensures a successful collaborative environment. As ontologies function as the catalyst in a collaborative environment, they create a common ground that empowers teams to seamlessly communicate, share information, overcome diverse terminology challenges, and foster cohesive and efficient collaboration. As a result, data flows seamlessly, enabling contributors to navigate the project and work toward shared objectives/goals.

2.3 Ontology in Design and Manufacturing

Researchers have utilized ontologies in design and manufacturing in the domain of design and manufacturing. Sanya and Shehab (2015) introduced a framework tailored for the aerospace sector, focusing on developing modular and reusable engineering design ontologies to enhance knowledge management, reduce maintenance workload, and promote the reuse of ontology knowledge across different projects within the aerospace industry [26]. Moreover, Arista et al. (2023) presented an ontology-based engineering system for aerospace manufacturing as a countermeasure to the deficiencies in existing Reconfigurable Manufacturing Systems (RMS) design approaches within the aerospace sector [27]. They illustrated the use of ontologies in collaborative engineering for the aerospace RMS design and highlighted its prospective implementation in practical scenarios.

Researchers have also employed ontologies in materials design databases that could be used in aerospace engineering. Li et al. (2020) introduced the Materials Design Ontology (MDO) to address challenges in the materials design field, where they used ontologies to formalize the representation of domain knowledge and ensured enhanced data interoperability across databases with diverse models [28]. Informed by materials science and guided by materials design databases, the MDO was applied to materials data from well-established databases. Furthermore, Lambrix et al. (2023) focused on overcoming challenges related to accessing and integrating data from diverse computational materials databases using ontologies [29]. The research used the MDO to enhance database interoperability. The paper details the ontology's development, content, and application, featuring a proof-of-concept implementation for data access and integration.

The materials design database [28] and portfolio management [30], [31] are intricately linked, as users of the database must strategically leverage material data for optimal decision-making and resource allocation [32], [33], [34]. To this end, the significance of ontologies in both material design database and portfolio management cannot be emphasized enough. Ontologies play a pivotal role by offering a structured depiction of knowledge within a specific domain, encapsulating crucial concepts and relationships. Consequently, ontologies bear significant relevance in modern research and industrial applications within design and manufacturing.

2.4 Heuristics, Taxonomies, and Lexicon as Components of Ontology Development

Adopting a heuristic approach (i.e., problem-solving or decision-making based on a practical rule of thumb) guided by ontology is paramount in engineering education due to complex and multifaceted challenges in real-world engineering scenarios [35]. In engineering education, heuristics not only nurture creativity and adaptability but also assist students in navigating the complexities of multidiscipline engineering without being constricted by predetermined algorithms or exhaustive analysis. Using heuristics allows an educational ontology to personalize students’ learning experiences, thereby tailoring educational content to the preferences of individual students [36]. Thus, implementing a heuristic approach instead of the model-based approach becomes a factor in successful education. To this end, research suggests using a combined heuristic and model-based approach, especially when the ontologies become a certain size and complexity when inconsistencies and unsatisfactory classes start occurring [37]. With the statements above, we know that a heuristic approach could be beneficial in some cases, especially when dealing with a complex problem where obtaining the optimal solution is impractical.

From the students' standpoint, learning involves connecting new information with existing knowledge. Research consistently emphasizes the positive influence of prior knowledge on acquiring new and interconnected information [38]. To simplify this, people acquire new knowledge by comparing it to what they already know. To this end, taxonomies and lexicons play a pivotal role in this dynamic [6], [7], aiding students in understanding connections through hierarchical (taxonomies) and linguistical (lexicon) arrangements of terms that capture the links between different fields of study.

Engineering educators must envision the educational landscape as an ecosystem, necessitating taxonomies to categorize the diverse components of engineering knowledge [39]. Simultaneously, lexicons contribute to standardizing technical terminology, which elevates and enriches the learning environment [40]. Thus, ontologies guide this diverse spectrum of educational elements, shaping a comprehensive and interconnected approach to aerospace engineering education.

2.5 Use of Ontology in Engineering Education System Development

Ontology integrations ensure a more robust and unified understanding across system elements. Fox (2021) utilized ontology engineering to create education system measurement definitions, such as the student/teacher ratio, following the ISO 37120 standard, to address indicator and data representation issues, providing consistent and streamlined educational system representations [41]. Since the engineering design process is multidisciplinary, engineering education curriculums must also transform from monodisciplinary to multidisciplinary. Butt et al. (2018) introduced a methodology for the development of ontologies for major engineering disciplines while emphasizing the necessity of an engineering ontology for a standard engineering design process and proposing a high-level transdisciplinary ontology model for engineering education [42].

Additionally, curriculum development and integration in engineering education have employed an ontological approach. Bussemaker et al. (2017) presented a method for continuous reflection and evolution of chemical engineering curricula, utilizing ontology to model topics, modules, and learning outcomes, demonstrating its effectiveness in curriculum development and integration through a case study [43]. Moreover, proposing the digital transformation of the transportation engineering program, Khabarova and Volegzhanina (2022) advocated for an ontology-based concept and tools, emphasizing that standardizing education content through ontological concepts and relations enables the development of web applications like intelligent tutoring agents [44].

2.6 A Research Gap

The literature review shows that there has been limited exploration of the application of ontologies in aerospace engineering education. Moreover, most ontology initiatives have been driven by instructors (a top-down approach) rather than originating from students themselves (a bottom-up approach). Therefore, this study examines the viability of incorporating ontologies into aerospace engineering education while investigating ontology integration in both the instructor-led top-down and the student-led bottom-up approaches.

3. Methodology

3.1 Description of Aerospace Engineering Disciplines at Purdue University

In the School of Aeronautics and Astronautics at Purdue University [45], the aerospace engineering program classifies its education components into the following segments: aerodynamics, aerospace systems design, astrodynamics and space applications, autonomy and control, propulsion, and structures and materials. Given the multidisciplinary nature of the aerospace field described above, effective education hinges on creating an environment where students can grasp individual concepts from these diverse segments and comprehend their interconnectedness. In this educational blueprint, ontology emerges as a fundamental framework for shaping the future of engineering education.

3.2 Two Approaches: Top-down vs. Bottom-up

Two distinct methodologies emerge in education ontology development: top-down and bottom-up approaches. In traditional definition, a top-down ontology refers to development that initiates by defining the most general concepts, establishing the foundational framework, and then specializing them as necessary [46], [47]. Conversely, the bottom-up approach involves defining the most specific concepts and capturing the specifics, then organizing them into more general classes as a cohesive structure emerges [46], [47].

On the other hand, our proposed definition slightly diverges from this traditional definition. In our context, top-down and bottom-up refer to the entities creating and providing ontologies. When instructors create and provide ontological context to students, laying out foundational concepts, this is our proposed top-down approach. Conversely, when students create and provide ontological context to instructors, contributing detailed insights, this is our proposed bottom-up approach.

Figure 1 depicts our proposed concepts. The section below elaborates on how we interpret and incorporate these approaches into ontology usage in engineering education. While our interpretation may diverge from the traditional definition of ontology development, we maintain the overarching concept of incorporating ontologies in education settings using top-down and bottom-up approaches.

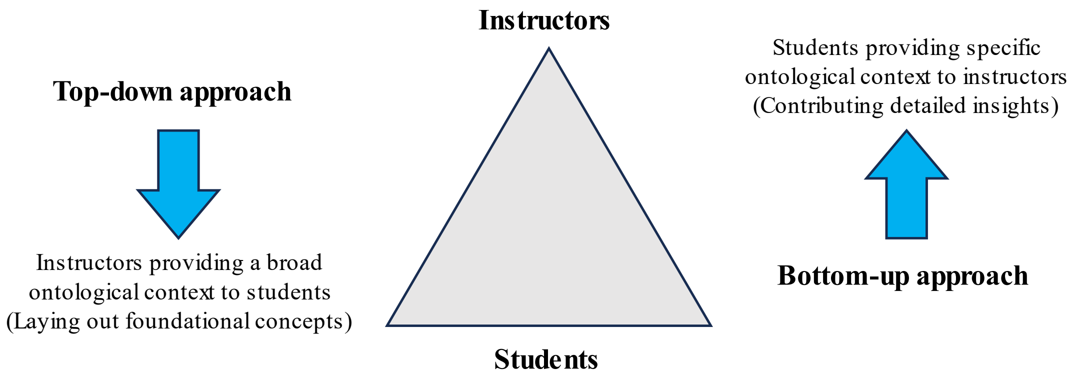

Figure 1 Top-down and Bottom-up Approaches in Ontology Integration

3.3 Top-down Approach: Instructor-led Ontology Integration

Adopting a top-down approach involves educators proactively creating and providing ontologies for students. The early introduction of comprehensive ontology is a foundational pillar, significantly elevating students' overall comprehension of the subject matter. We can further optimize this strategic integration of ontologies by coupling them with assignments that link course concepts to other coursework in current and future semesters.

By doing so, educators create a dynamic learning environment that transcends traditional boundaries. This holistic approach not only addresses the perennial "so what" problem (i.e., relevance challenges for students) but also guides students beyond the mere acquisition of isolated theoretical insights (i.e., more profound understanding for students). It encourages a more profound knowledge of the practical implications of their studies, thereby fostering a comprehensive and interconnected perspective that contributes to a richer educational experience.

This pedagogical framework, rooted in the top-down approach of introducing ontologies, goes beyond conventional teaching methodologies by allowing students to perceive and engage with the broader context. Understanding how different elements fit together is crucial for students' academic growth, and the ontology approach facilitates this by providing a structured and interconnected view of the subject matter. Embracing this approach enhances students' comprehension and catalyzes creativity in their academic pursuits. The interconnected view encourages students to think innovatively, drawing meaningful connections between seemingly disparate concepts. This mindset shift is instrumental in cultivating a generation of aerospace engineers who are not only well-versed in individual theories but also possess the creativity to apply their knowledge to real-world challenges. Drawing parallels with the reported effectiveness of a SoS inspired framework in engineering education [48], it becomes evident that the ontology approach holds immense potential to positively influence the understanding of individual subjects and contribute to the broader landscape of aerospace engineering education.

3.4 Bottom-up Approach: Student-led Ontology Integration

In the evolving landscape of education, hands-on learning experiences are increasingly valued, and integrating ontology construction into class projects offers a promising avenue for deepening students' understanding of complex subjects. Implementing class projects that involve ontology construction could enhance students' learning process. To this end, aerospace engineering students could progressively build their "ontology portfolio" each semester, culminating in a comprehensive senior-year portfolio, integrating the entire undergraduate engineering coursework into cohesive ontologies. Research showed that empowering students is a practical approach to engineering education [49]. Given the diverse subjects covered in undergraduate aerospace engineering studies, this approach offers students a holistic understanding of interdisciplinary connections within aerospace engineering. In other words, a comprehensive ontology for aerospace engineering coursework could enhance learning by going beyond the boundaries of individual courses and encouraging deeper connections among diverse subjects that the students studied during their undergraduate studies.

To further support this initiative, we propose integrating ontologies into the framework of senior capstone projects. Notably, this approach offers a straightforward way to implement ontologies into existing coursework, requiring only the addition of ontological requirements to course objectives. Through rigorous engagement with ontology construction, students would enhance their understanding of course material and significantly contribute to the collective knowledge base of aerospace engineering. Active involvement in ontology construction is critical to fostering a more enriched and interconnected educational experience.

4. Results and Discussion

4.1 Top-down Approach: Instructor Providing Conceptual Framework in Aerospace Structures and Materials Education

Figure 2 depicts the representation of the top-down approach. In this section, we will discuss how instructors can provide an ontological context of plane stress analysis (i.e., two-dimensional stress analysis), one of the key topics in aerospace structures and materials, to lay out its foundational concept to help students to understand the subject matter.

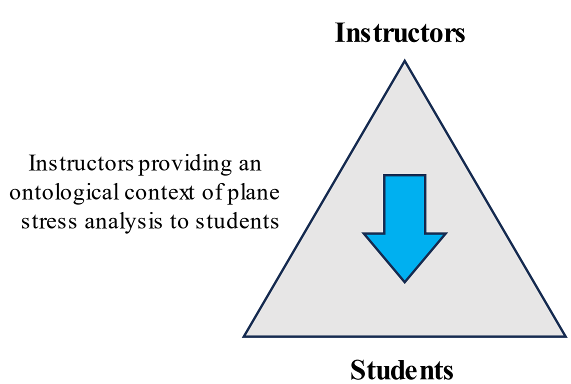

Figure 2 Top-down Approach Representation

Engineering topics rely heavily on mathematics. Therefore, engineering instructors must integrate mathematical concepts while skillfully presenting engineering topics. In AAE 20400 Aeromechanics II and AAE 35200 (i.e., structures and materials courses in aerospace engineering) at Purdue University [50], [51], [52], our pedagogy introduces students to the concept of 2D Mohr's circle. This graphical approach depicts the plane stress state, which is a stress state in a thin structure. An advantage of this approach is that it empowers students to utilize a manual, graphical method, allowing them to visualize stress states using a circle that they sketch on a piece of paper and to determine principal stresses (i.e., maximum and minimum normal stresses) and principal directions (i.e., orientations of the planes on which these stresses act).

In addition to the graphical approach mentioned earlier, our pedagogy incorporates eigenvalues and eigenvectors, employing a mathematical method to determine principal stresses and directions. While this mathematical approach lacks a direct visual representation, it equips students with the ability to apply mathematical concepts in engineering contexts, transforming seemingly abstract notions into practical tools. Undergraduate aerospace engineering students typically encounter eigenvalues and eigenvectors in MA 26500 Linear Algebra as part of their curriculum. Consequently, the analysis of plane stress conditions bridges into linear algebra, highlighting the interconnectedness between the mathematical approach (eigenvalues and eigenvectors) and the engineering approach (Mohr's circle) in analyzing plane stress scenarios. This foundational relationship can be effectively represented within ontological frameworks, as depicted in Figure 3.

We use eigenvalues and eigenvectors based on the stress tensor to better understand this relationship. The stress tensor represents the stress state within a material at a point. By solving the equation (i.e., a characteristic equation) derived from the stress tensor, we can determine eigenvalues indicating principal stresses. Additionally, eigenvectors reveal the directions of these stresses. In the context of Mohr's circle analysis mentioned earlier, the eigenvalues (representing magnitudes of maximum and minimum stresses) directly correspond to the points where the circle intersects the horizontal axis. Similarly, eigenvectors (representing directions of maximum and minimum stresses) correspond to half of the angle formed between the horizontal axis and a line connecting two points on the circle. These two points represent the given plane stress conditions of a structure.

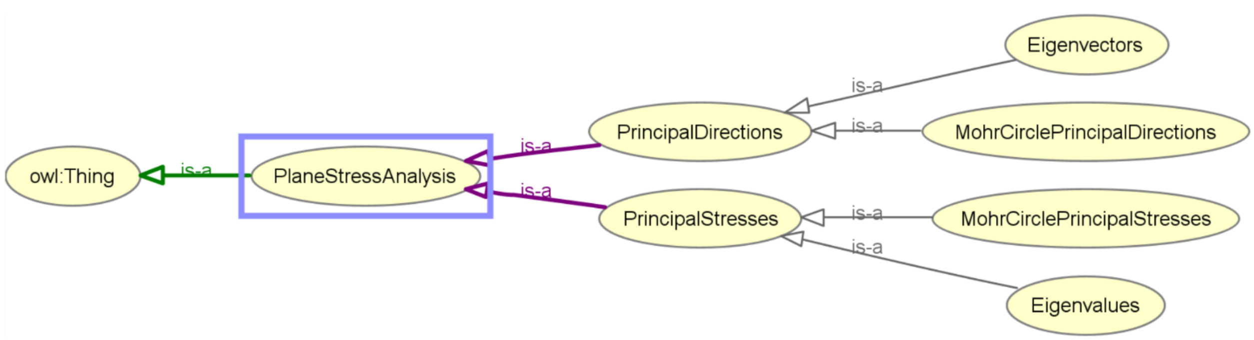

Figure 3 Example of Ontology Use in Aerospace Structures and Materials Education

Integrating eigenvalues and eigenvectors analysis with Mohr's circle analysis illustrates the interdisciplinary nature inherent in these mathematical and engineering principles. Together, they constitute a fundamental framework for dissecting the complexities of physical systems within the structures and materials discipline. By leveraging the capabilities of both the mathematical approach (eigenvalues and eigenvectors) and the engineering approach (Mohr's circle), students gain profound insights into material behavior under plane stress, enabling the prediction of failure modes and the design of efficient and inherently safer structures. This underscores the importance of incorporating these concepts into ontological frameworks, as they play a pivotal role in fostering more profound understanding and meaningful connections within the engineering discipline of structures and materials. Bringing these concepts together not only enhances student understanding but also perfectly aligns with the collaborative spirit of modern engineering education, where different fields often intersect in dynamic and innovative ways.

4.2 Bottom-up Approach: Students Providing Detailed Insights in Outer Space Exploration

Figure 4 depicts the representation of the bottom-up approach. In this section, we will discuss how students can provide an ontological context of life support systems, one of the key topics in outer space exploration, to contribute detailed insights into the system. By this exercise, students can develop a comprehensive knowledge of how different parts of systems are connected.

Undergraduate study generally concludes with a comprehensive project, such as a senior capstone project. These projects serve as a culminating experience for students, designed to demonstrate the application of knowledge they learned across various disciplines. One of the popular topics for engineering students, especially those specializing in aerospace engineering, is outer space exploration, like those seen in the NASA Artemis program [53], [54], [55]. These initiatives offer students a practical chance to acquire firsthand experience in space exploration and research. Projects like this also motivate students due to the possibility of aiding the progress of space innovation.

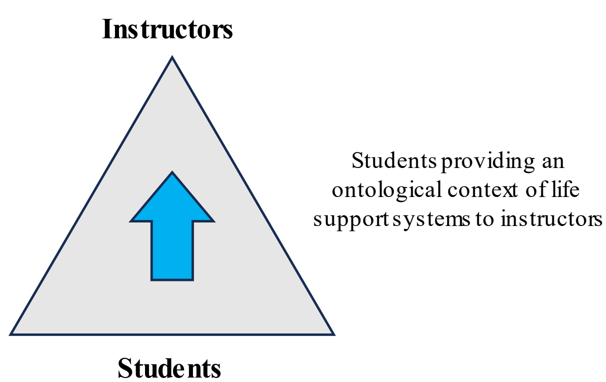

Figure 4 Bottom-up Approach Representation

One of the prominent topics within outer space exploration is the sustainable human presence on Mars [56], [57]. Within this domain, the challenge is to develop robust life support systems vital for ensuring a lasting human presence on Mars because of the planet's unforgiving and harsh environment. There are some challenges like space suits to shield the human body from radiation [58], basic needs like air and water via Environmental Control and Life Support Systems (ECLSS) [59], greenhouses to grow plants for consumption [60], and low-maintenance animal (e.g., chicken and rabbits) for meat consumption [61]. Students can use ontologies to visualize the life support systems, subsystems, and relationships, as depicted in Figure 5.

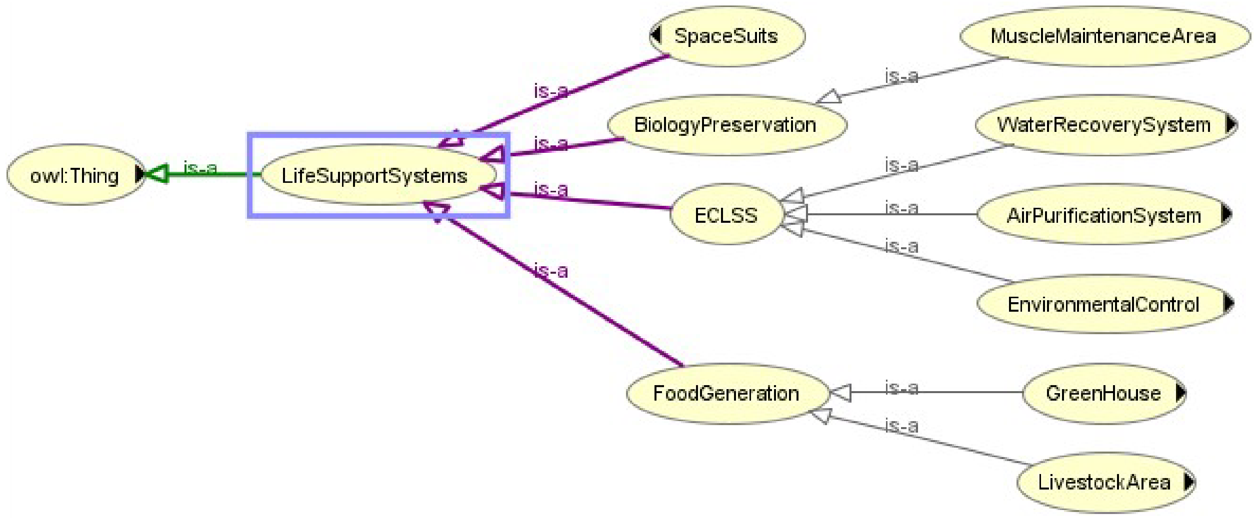

Figure 5 Example of Ontology Use in a Student Project on Outer Space Exploration

Utilizing ontologies to depict Mars' life support systems offers several advantages. Ontologies effectively organize and manage complex information about life support systems, defining the types of entities and their relationships within the system. This structuring enables users to better understand and manage the various components and their potential interactions. Additionally, software applications managing these systems can benefit from ontologies, as they formally define a structured collection of classes of entities, their interconnections, and their characteristics [62]. In summary, integrating ontological perspectives into aerospace engineering education facilitates holistic knowledge enrichment, encourages students' hands-on experience, and drives them to push the boundaries of space innovation. In this bottom-up framework, students can actively contribute intricate insights into areas such as life support systems for outer space exploration.

5. Conclusions and Future Directions

Our study investigated the integration of ontology into aerospace engineering education and proposed top-down and bottom-up approaches. The top-down approach involves educators providing students with ontological context to help them understand the subject. On the other hand, the bottom-up approach involves students contributing their insights into subjects, which helps them further develop a comprehensive knowledge of the subject while demonstrating the knowledge to the instructors.

For future work, we seek more examples of use cases to demonstrate the potential use of the ontologies in different contexts. For instance, we can envision the possibility of implementing a dedicated one-credit senior-level course designed to formalize and consolidate students' ontology-building efforts. Such an initiative would significantly bolster the incorporation of ontologies into undergraduate studies, thereby fostering a comprehensive and interconnected perspective that contributes to a richer educational experience. From the perspective of scholarship of teaching and learning (SoTL) research, we are keen on exploring how an ontology-driven approach influences students' grasp of subject matter. Findings from SoTL research could furnish statistical evidence showcasing the efficacy of the ontology-inspired framework in engineering education.

References

[1] D. A. DeLaurentis, K. Moolchandani, and C. Guariniello, *System of Systems Modeling and Analysis*. CRC Press, 2022.

[2] W. Tsutsui *et al.*, "Mechanical energy dissipation in a multifunctional battery system," *MRS Adv*, vol. 1, no. 6, pp. 381–388, 2016, doi: 10.1557/adv.2016.39.

[3] W. Tsutsui, T. Siegmund, N. D. Parab, H. Liao, T. N. Nguyen, and W. Chen, "State-of-Charge and Deformation-Rate Dependent Mechanical Behavior of Electrochemical Cells," *Exp Mech*, 2017, doi: 10.1007/s11340-017-0282-2.

[4] W. Tsutsui, H. Liao, Y. Feng, T. Siegmund, and W. Chen, "Quasistatic and dynamic mechanical responses of load-bearing structural batteries for electric vehicles," in *Society of Engineering Science 51st Annual Technical Meeting*, West Lafayette, IN, Oct. 2014. [Online]. Available: https://docs.lib.purdue.edu/ses2014/mss/mmms/14/

[5] W. Tsutsui, Y. Feng, W. W. Chen, and T. H. Siegmund, "Impact resistant battery enclosure systems," U.S. Patent No. 11,050,114 B2, Jun. 2021

[6] D. A. DeLaurentis, "A taxonomy-based perspective for systems of systems design methods," in *2005 IEEE international conference on systems, man and cybernetics*, 2005, pp. 86–91.

[7] D. DeLaurentis and R. K. Callaway, "A system-of-systems perspective for public policy decisions," *Review of Policy research*, vol. 21, no. 6, pp. 829–837, 2004.

[8] N. Guarino, D. Oberle, and S. Staab, "What Is an Ontology?," *Handbook on Ontologies*, pp. 1–17, 2009, doi: 10.1007/978-3-540-92673-3_0.

[9] Oxford English Dictionary, "https://www.oed.com/."

[10] T. R. Gruber, "A translation approach to portable ontology specifications," *Knowledge Acquisition*, vol. 5, no. 2, pp. 199–220, Jun. 1993, doi: 10.1006/KNAC.1993.1008.

[11] Z. Ming *et al.*, "Ontology-based representation of design decision hierarchies," *J Comput Inf Sci Eng*, vol. 18, no. 1, p. 11001, 2018.

[12] W. N. Borst, "Construction of engineering ontologies for knowledge sharing and reuse.," 1999.

[13] M. W. Maier, "Architecting Principles for Systems-of-Systems," *Systems Engineering: The Journal of the International Council on Systems Engineering*, vol. 1, no. 4, pp. 267–284, 1998.

[14] T. R. Gruber, "Toward principles for the design of ontologies used for knowledge sharing?," *Int J Hum Comput Stud*, vol. 43, no. 5–6, pp. 907–928, 1995.

[15] N. M. Matasyoh, G. Okeyo, and W. Cheruiyot, "Ontology-driven approach for knowledge sharing and retrieval," *International Journal of Computer Science Issues (IJCSI)*, vol. 13, no. 4, p. 59, 2016.

[16] M. A. Osman, S. A. M. Noah, and S. Saad, "Ontology-based knowledge management tools for knowledge sharing in organization—a review," *IEEE Access*, vol. 10, pp. 43267–43283, 2022.

[17] J. S. Osmundson, T. V Huynh, and P. Shaw, "Developing ontologies for interoperability of systems of systems," in *Conference on Systems Engineering Research*, 2006.

[18] L. Knöös Franzén, “An Ontological and Reasoning Approach to System of Systems,” Linköping University Electronic Press, 2021.
[19] D. A. DeLaurentis, “Understanding Transportation as System-of-Systems Design Problem,” in *43rd AIAA Aerospace Sciences Meeting and Exhibit - Meeting Papers*, 2005, pp. 15083–15096. doi: 10.2514/6.2005-123.
[20] W. Tsutsui, E. J. Williamson, K. Park, and M. D. Sangid, “Pedagogy Improvement in Aerospace Structures Education Using Virtual Labs: Before, During, and After the COVID-19 School Closures and Remote Learning,” in *2021 ASEE Virtual Annual Conference Content Access, Virtual Conference*, Jul. 2021. doi: 10.18260/1-2--37569.
[21] W. Tsutsui *et al.*, “Enhancing Students’ Understanding of Deformation and Stress in Aerospace Structures Education via Virtual Labs,” in *2022 ASEE Annual Conference & Exposition*, Minneapolis, MN, Aug. 2022. doi: 10.18260/1-2--41810.
[22] I. N. Athanasiadis, A.-E. Rizzoli, S. Janssen, E. Andersen, and F. Villa, “Ontology for seamless integration of agricultural data and models,” in *Research conference on metadata and semantic research*, 2009, pp. 282–293.
[23] T. Gruber, “What is an Ontology.” 1993.
[24] P. M. Clarke *et al.*, “Refactoring software development process terminology through the use of ontology,” in *Systems, Software and Services Process Improvement: 23rd European Conference, EuroSPI 2016, Graz, Austria, September 14-16, 2016, Proceedings 23*, 2016, pp. 47–57.
[25] R. Hoehndorf, P. N. Schofield, and G. V Gkoutos, “The role of ontologies in biological and biomedical research: a functional perspective,” *Brief Bioinform*, vol. 16, no. 6, pp. 1069–1080, 2015.
[26] I. O. Sanya and E. M. Shehab, “A framework for developing engineering design ontologies within the aerospace industry,” *Int J Prod Res*, vol. 53, no. 8, pp. 2383–2409, 2015.
[27] R. Arista, F. Mas, D. Morales-Palma, and C. Vallellano, “An Ontology-based Engineering methodology applied to aerospace Reconfigurable Manufacturing Systems design,” *Int J Prod Res*, pp. 1–19, 2023.
[28] H. Li, R. Armiento, and P. Lambrix, “An ontology for the materials design domain,” in *International Semantic Web Conference*, 2020, pp. 212–227.
[29] P. Lambrix, R. Armiento, H. Li, O. Hartig, M. Abd Nikooie Pour, and Y. Li, “The materials design ontology,” *Semant Web*, no. Preprint, pp. 1–35, 2023.
[30] W. Tsutsui *et al.*, “Model-based Approach in Defense Portfolio Management: Data Preparation, Analysis, and Visualization of Decision Spaces,” 2023. [Online]. Available: https://dair.nps.edu/handle/123456789/4849
[31] C. Guariniello, P. Uday, W. Tsutsui, and K. Marais, “System of Systems Analytic Workbench,” *Systems Engineering for the Digital Age: Practitioner Perspectives*, pp. 601–635, 2023, doi: 10.1002/9781394203314.ch29.
[32] W. Tsutsui *et al.*, “Decision Making for Additive Manufacturing in Sustainable Defense Acquisition,” *Naval Engineers Journal*, vol. 135, no. 4, pp. 47–58, 2023.
[33] C. Guariniello, W. Tsutsui, D. Bekdache, and D. DeLaurentis, “Digital Engineering Transformation: A Case Study,” *Systems Engineering for the Digital Age: Practitioner Perspectives*, pp. 241–266, 2023, doi: 10.1002/9781394203314.ch12.
[34] J. Panchal, W. Tsutsui, M. Atallah, R. Malak, N. Hartman, and D. DeLaurentis, “Mission-Aware Integrated Digital Transformation for Operational Advantage,” 2023.

[35] H. Wang, M. Horridge, A. Rector, N. Drummond, and J. Seidenberg, "Debugging OWL-DL ontologies: A heuristic approach," in *The Semantic Web–ISWC 2005: 4th International Semantic Web Conference, ISWC 2005, Galway, Ireland, November 6-10, 2005. Proceedings 4*, 2005, pp. 745–757.
[36] W. Villegas-Ch and J. Garcia-Ortiz, "Enhancing Learning Personalization in Educational Environments through Ontology-Based Knowledge Representation," *Computers*, vol. 12, no. 10, p. 199, 2023.
[37] P. Rodler, "One step at a time: An efficient approach to query-based ontology debugging," *Knowl Based Syst*, vol. 251, p. 108987, 2022.
[38] W. M. Cohen and D. A. Levinthal, "Absorptive capacity: A new perspective on learning and innovation," *Adm Sci Q*, pp. 128–152, 1990.
[39] S. G. Yildirim and S. W. Baur, "Development of learning taxonomy for an undergraduate course in architectural engineering program," in *American Society for Engineering Education*, 2016, pp. 1–10.
[40] L. J. R. Lawless and G. V Civille, "Developing lexicons: A review," *J Sens Stud*, vol. 28, no. 4, pp. 270–281, 2013.
[41] M. S. Fox, "An ontology engineering approach to measuring city education system performance," *Expert Syst Appl*, vol. 186, p. 115734, 2021.
[42] M. Butt, A. Sharunova, M. Storga, Y. I. Khan, and A. J. Qureshi, "Transdisciplinary engineering design education: Ontology for a generic product design process," *Procedia CIRP*, vol. 70, pp. 338–343, 2018.
[43] M. Bussemaker, N. Trokanas, and F. Cecelja, "An ontological approach to chemical engineering curriculum development," *Comput Chem Eng*, vol. 106, pp. 927–941, 2017.
[44] V. Khabarov and I. Volegzhanina, "An impact of ontology-based service-oriented ecosystems on digital transformation of railway transport and engineering education," *Transportation Research Procedia*, vol. 63, pp. 1899–1908, 2022.
[45] Purdue University, "https://www.purdue.edu/."
[46] M. Uschold and M. Gruninger, "Ontologies: Principles, methods and applications," *Knowl Eng Rev*, vol. 11, no. 2, pp. 93–136, 1996.
[47] N. F. Noy, D. L. McGuinness, and others, "Ontology development 101: A guide to creating your first ontology." Stanford knowledge systems laboratory technical report KSL-01-05 and~…, 2001.
[48] W. Tsutsui and D. Delaurentis, "A System-of-Systems Inspired Framework to Enhance Aerospace Structural Mechanics Education," in *2023 ASEE Annual Conference & Exposition*, 2023. doi: 10.18260/1-2--42518.
[49] D. Schaefer, J. Panchal, S. Haroon, and F. Mistree, "Design Education for the World of Near Tomorrow: Empowering Students to Learn How to Learn," in *2011 ASEE Annual Conference & Exposition*, 2011, pp. 22–429.
[50] W. Tsutsui, R. D. Lopez-Parra, G. S. Coutinho, A. Mello, M. D. Sangid, and T. J. Moore, "The Implementation of Virtual Labs in Aerospace Structures Education," in *2020 ASEE Virtual Annual Conference*, 2020. doi: 10.18260/1-2--35339.
[51] W. Tsutsui and M. C. Loui, "The Effectiveness of Weekly Supervised Homework Sessions in an Aerospace Structural Mechanics Course," in *2016 ASEE Annual Conference & Exposition*, New Orleans, LA, 2016. doi: 10.18260/p.26145.
[52] W. Tsutsui and M. C. Loui, "The Impact of Supervised Homework Sessions and SAT-Math Scores on Academic Performance in an Advanced Undergraduate Course," in

Proceedings - Frontiers in Education Conference, FIE, 2016. doi: 10.1109/FIE.2016.7757431.

[53] D. Folta and T. Sweetser, "ARTEMIS mission overview: from concept to operations," in *American Astronautical Society/American Institute of Aeronautics and Astronautics (AAS/AIAA) Astrodynamics Specialist Conference*, 2011.

[54] M. Smith *et al.*, "The artemis program: An overview of nasa's activities to return humans to the moon," in *2020 IEEE Aerospace Conference*, 2020, pp. 1–10.

[55] S. Creech, J. Guidi, and D. Elburn, "Artemis: An overview of NASA's activities to return humans to the moon," in *2022 IEEE Aerospace Conference (AERO)*, 2022, pp. 1–7.

[56] D. Rapp, *Human missions to Mars*. Springer, 2007.

[57] E. Marandola *et al.*, "Exploration Systems Requirements to Establish a Sustainable Human Presence on Mars," in *AIAA SPACE and Astronautics Forum and Exposition*, 2017, p. 5367.

[58] Y. Akisheva and Y. Gourinat, "Utilisation of moon regolith for radiation protection and thermal insulation in permanent lunar habitats," *Applied Sciences*, vol. 11, no. 9, p. 3853, 2021.

[59] J. Metcalf, L. Peterson, R. Carrasquillo, and R. Bagdigian, "National aeronautics and space administration (NASA) environmental control and life support (ECLS) integrated roadmap development," in *42nd International Conference on Environmental Systems*, 2012, p. 3444.

[60] S. Moffatt, R. Morrow, and J. Wetzel, "Astro GardenTM aeroponic plant growth system design evolution," 2019.

[61] N. Kanas, "Artemis and the Psychosociology of Lunar Colonies," in *Behavioral Health and Human Interactions in Space*, Springer, 2023, pp. 299–329.

[62] D. A. O'Neil and R. J. Rovetto, "An Ontology-Based Virtual Orrery," 2021.