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AN ONTOLOGY FOR REPRESENTING CRAWLER CRANE OPERATIONAL SPACE REQUIREMENT ON SEMANTIC WEB

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and Mohammed Adel Abdelmegid[5]

ABSTRACT

Lookahead planning incorporates checking and removing operational constraints to develop achievable plans. The manual constraint-checking process is arduous because (1) Construction constraints are dynamic due to constantly changing project conditions, and (2) The information concerning constraints, e.g., attributes and status, are dispersed across heterogeneous databases. While semantic web technology has been used to automate constraint-checking and address these issues, space constraints, e.g., space needed for resource operation, have often been ignored. Cranes are crucial construction resources, necessitating checking of associated space constraints for developing constraint-free lookahead plans. Representing crane operational space requirements on the semantic web should be the first step for such checking. However, existing ontologies cannot do so.

This study aims to develop a Crane Space Representation Ontology (CSRO) to represent different components of the operational space of a crawler crane with a lattice boom. Built using Ontology Development 101 methodology, CSRO includes four classes, 19 subclasses, nine object properties, and seven datatype properties, representing crane operational space with diverse geometries like bounding box, cylinder, and cone. Automated consistency checking and task-based evaluation confirm the CSRO's consistency and effectiveness in addressing the competency questions regarding various aspects of space requirements for crane operation.

KEYWORDS

Last Planner® System, Lookahead Planning, Constraint Analysis, Semantic Web, Crawler Crane.

INTRODUCTION

Lookahead Planning (LAP) is a key stage in the Last Planner® System (LPS) (Ballard, 2000). It consists of three steps, i.e., task breakdown (breaking down the work processes into operations), constraint management (identification, checking, and removal of constraints associated with the operations), and design of operations (scheduling the operations according

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to constraint status) (Hamzeh et al., 2012). Effective constraint management is crucial for continuous workflow, improved task preparation, and schedule adherence on construction projects (Lagos & Alarcón, 2021). However, constraint management lacks appropriate implementation (Dave et al., 2015) due to the complexity and dynamic nature of construction projects (Soman et al., 2020). To this end, attempts have been made to utilize automated data-driven approaches to support constraint management, such as semi-automated constraint identification (Zaeri et al., 2017), tracking the status of constraints (Xiao et al., 2021), and constraint checking in the schedules (Soman et al., 2020).

Constraint checking is the process of checking if the prerequisites for the scheduled activities are complete, which is critical to ensure that only achievable activities are committed (Soman et al., 2020). Most existing automated constraint-checking approaches related to schedules do not apply to the LAP process. These studies usually utilize Building Information Models (BIM) and construction schedules as the main sources of information for rule checking (Ji & Leite, 2018). However, the situations in construction projects are everchanging, and such dynamically changing constraint information is distributed in heterogeneous databases with different stakeholders (Soman et al., 2020), resulting in BIM being an insufficient source of information for constraint checking. To this end, Soman et al. (2020) developed a linked data based constraint checking system. Linked data offers an opportunity to connect cross-domain data in a machine-readable manner and make logical inferences from it (Pauwels, Zhang, et al., 2017). However, they fell short in checking space-related constraints, such as safety and site layout, which are essential in lean construction (Ballard, 2000).

Checking and removing space constraints in LAP is crucial for the seamless execution of construction projects to eliminate or minimize the waste of resources (Akinci et al., 2002). Different types of space-related constraints can be found on construction projects, including space requirements for working of resources, storing materials, and installing temporary facilities on site. Cranes are crucial for space constraint checking perspective in construction, as many activities rely on them for material lifting and transfer. Further, cranes have very high monetary implications on the overall project cost, necessitating their efficient use (Aghajamali et al., 2023). Thus, checking space constraints related to operations involving cranes is essential for generating reliable lookahead schedules. Similar to other constraints, the existing efforts towards checking such space constraints related to cranes mainly utilized 3D models and centralized databases as primary sources of information (Aghajamali et al., 2023). Further, such approaches failed to incorporate the dynamics of construction sites quickly (Hussein & Zayed, 2021), restricting their applicability in LAP.

Linked data facilitates addressing this gap by semantically interlinking heterogeneous datasets such as-built data collected using automated data collection technologies, BIM models, constraint information, and construction schedules to perform constraint checking. Performing such constraint checking requires all the information to be represented on the semantic web (Soman et al., 2020) with the help of ontologies. According to Gruber (1995), an ontology is *"an explicit specification of a conceptualization"*. It provides a way to formally describe the knowledge in a domain using concepts and their relationships. Several ontologies exist in the construction domain that can represent information, such as schedules (Farghaly et al., 2024), building topology (Rasmussen et al., 2021), and product-related information (Wagner et al., 2022). However, existing ontologies cannot represent the information related to the detailed operational space requirements of the cranes. This creates a bottleneck in performing linked data based space constraint-checking of crane-dependent operations in lookahead schedules.

To address this gap, this study aims to develop a Crane Space Representation Ontology (CSRO) to represent the space required by a crane to perform its lifting operation in a construction project. The scope of this study is limited to mobile crawler cranes with lattice booms, as they are commonly used in construction projects (Aghajamali et al., 2023).

LITERATURE REVIEW

SEMANTIC WEB AND LINKED DATA IN CONSTRUCTION

The semantic web is a transformation from the web of documents to the web of data, where the data is represented in a semantically interlinked and machine-readable manner (Berners-Lee et al., 2001). Linked data is a set of principles for representing the data on the semantic web in the form of subject-predicate-object triples.

Owing to the potential of semantic web technology to improve data interoperability, it has been extensively adopted in requirement checking from heterogeneous data. Pauwels, Van Deursen, et al. (2011) used the semantic web to check the acoustic performance regulations on building data. Fitkau & Hartmann (2024) checked safety regulations using the semantic web. However, limited attention has been given to checking the constraints that can prevent construction activities from being executed. Cao et al. (2022) developed an approach to check constraints related to the manufacturability of prefabricated components, such as resource availability, space availability, and lead time. However, they did not consider constraints related to space requirements for the operations of construction equipment. Soman et al. (2020) utilized linked data to check various constraints in lookahead schedules, such as cardinality, resource availability, and precedence. However, they used ifcOWL ontology (an ontology to represent Industry Foundation Class (IFC) data schema in Web Ontology Language (OWL)) to represent site and schedule data, which, is not well suited for performing reasoning on geometric data (Pauwels, Krijnen, et al., 2017).

ONTOLOGIES FOR REPRESENTING CONSTRUCTION SITE ELEMENTS

Ontologies act as the foundation over which the semantic web technology is built. They provide a common understanding of a domain, supporting interoperability between different applications (Farghaly et al., 2024). Ontologies are built using components such as classes, subclasses, and properties. Classes represent a collection of entities having common characteristics. Classes may contain subclasses, which represent more specific entities than classes and inherit the characteristics from classes. Properties provide additional information about the classes to furnish a complete description of intended knowledge (Noy & McGuinness, 2001). Several ontologies have been proposed to represent construction site-related data on the semantic web.

Being fundamentally based on IFC, ifcOWL is limited to the constructs defined in IFC. The Building Topology Ontology (BOT) is a domain ontology used to represent the topological relationships between building components (Rasmussen et al., 2021). The BIM Shared Ontology (BIMSO) represents BIM data related to buildings, which can be used for developing domain-specific ontologies such as design and scheduling (Niknam & Karshenas, 2017). The Building Product Ontology (BPO) focuses on describing singular instances of products that can be part of the building (Wagner et al., 2022). The Digital Construction Ontologies (DiCon) support formally representing and integrating the information related to construction workflow (Zheng et al., 2021). DiCon comprises an 'entity' module related to construction site elements such as equipment. Several ontologies facilitate safety regulation checking in construction, by representing site elements like equipment, materials, and personnel (Li et al., 2022).

The utility of the above-mentioned ontologies for performing space constraint checking related to cranes is limited for two reasons: (1) Only a few of the above-mentioned ontologies have classes, like construction equipment, that can be instantiated with construction cranes. (2) These studies addressed construction equipment at a general level, where the representation of the space occupied by construction equipment on a site was limited to a bounding box covering the entire equipment in a fixed orientation. However, the operations of crawler cranes on construction sites are complex. They involve changing boom length, rotation of boom, rotation of mast, rotation of the main body, rotation of counterweights, possible rotation of the lifted object, and space required for outriggers, among others (Aghajamali et al., 2023; Olearczyk et al., 2014). Therefore, a new ontology is needed to perform accurate linked data based space constraint checking of operations involving cranes, which should consider different components of the space required by cranes to operate. To this end, this study develops CSRO to represent the space requirement of mobile crawler crane operations.

ONTOLOGY DEVELOPMENT METHODOLOGY

Ontology Development 101 (Noy & McGuinness, 2001) was utilized to guide the development of CSRO ontology. This methodology was selected because of its simplicity and feasibility to be used by inexperienced ontology designers (Noy & McGuinness, 2001), and its widespread use in the construction sector (Wu et al., 2021). This study utilizes the Protégé system, a widely used open-source environment for developing, storing, and maintaining the CSRO ontology. The ontology development was done by following the below-mentioned seven steps as described in Ontology Development 101. These steps include determining the domain and scope of the ontology, exploring the reusing existing ontologies, identifying important terms in the ontology, determining classes and class hierarchy, defining the properties associated with the classes, defining the facets of the properties, and creating instances.

CRANE SPACE REPRESENTATION ONTOLOGY

This section discusses the development of CSRO through the seven steps of Ontology Development 101.

STEP 1: DETERMINE THE DOMAIN AND SCOPE OF THE ONTOLOGY

Firstly, the ontology's scope, intended uses, end-users, and domain were determined. It was performed by answering the following fundamental questions within the context of this research (Noy & McGuinness, 2001):

1. What is the domain that ontology will cover?
   In this research, the representation of a mobile crawler crane's operational space requirement on a construction site is the domain of the CSRO ontology.

2. What is the purpose of the ontology?
   The CSRO ontology will be used to represent a crawler crane's space requirements in the context of a semantic web representation of a construction site, thus supporting space constraint checking for operations involving cranes on construction sites.

3. Who are the intended users and maintainers of the ontology?
   The end users of the CSRO ontology are construction planners involved in the lookahead scheduling of operations on construction projects.

4. What are the competency questions for the ontology?
   The competency questions are a set of questions that the knowledge base based on the ontology should be able to answer (Noy & McGuinness, 2001). To develop the competency questions for CSRO ontology, literature related to mobile crawler crane planning was reviewed. The literature included academic publications, textbooks, and practitioners’ guides related to mobile crawler cranes. The objective of the review was to identify the different components of the space requirement for the operation of the mobile crawler crane. The following competency questions were formulated for the development of CSRO ontology:

CQ1: What is the space required to place the crane at a particular location?
CQ2: What is the space required for the rotation of crane components such as the main body, boom, and counterweights of the crane?
CQ3: What is the space required for crane outriggers to be extended?
CQ4: What is the space required for the object to be lifted and its rotation while lifting?

STEP 2: CONSIDER REUSING EXISTING ONTOLOGIES

PURPOSE AND USE

Reusing existing ontologies can save time and effort in the ontology development process (Noy & McGuinness, 2001). To identify existing ontologies that can be reused to represent the knowledge related to crane space requirements, ontology libraries such as Ontobee, DARPA Agent Markup Language (DAML), and Linked Open Vocabularies (LOV) were searched. A literature search using Scopus was conducted to explore any research studies on crane ontology, as it is one of the most prominent literature databases (Hussein & Zayed, 2021). No specific ontology was found for the representation of the space requirement of the crawler cranes. However, some existing ontologies can generally represent construction equipment, which can be partially reused for crane representation. For instance, ifcOWL ontology has *IfcConstructionEquipmentResource* as a class, which can indicate construction equipment such as cranes. To represent spatial aspects of cranes, existing ontologies such as GeoSPARQL (*OGC GeoSPARQL – A Geographic Query Language for RDF Data*, 2011) and approaches such as Well Known Text (WKT) (Pauwels, Krijnen, et al., 2017) expressions were utilized in CSRO.

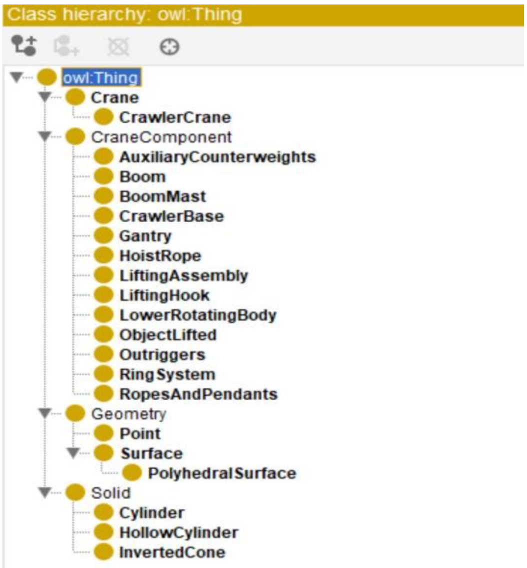
STEP 3: ENUMERATE IMPORTANT TERMS IN THE ONTOLOGY

Enumerating all the necessary terms is essential to ensure a complete representation of the intended knowledge. These terms make the foundation of class and class hierarchy development. To identify important terms for CSRO, this study utilized knowledge sources such as textbooks related to construction equipment (Peurifoy et al., 2018; Shapiro & Shapiro, 2010), literature concerned with crane space planning (Lei et al., 2013; Olearczyk et al., 2014) and web pages related to crawler crane components. The important terms identified for building CSRO consisted of two main aspects: (1) the terms related to crane components such as boom, boom mast, outriggers, and hoist rope, among others, and (2) the terms related to types of geometries used for representing crane space requirements, such as cylinder, cone, polyhedral surfaces, etc. Instead of considering each small component of the crane, only the prominent space-consuming components, whose bounding boxes incorporate the smaller crane components, were considered. For instance, elements like counterweights, the operator's cab, the winding drum (if present), the primary body of the crane, the engine unit (for crawler cranes), the access points, and walkways are considered together in a single component called 'Lower rotating body.' The meaning of each term was described in the ontology to ensure clarity during usage.

STEP 4: DEFINE CLASSES AND CLASS HIERARCHY

The classes and class hierarchy were defined from the identified key terms. A middle-out/combination development approach was used to this end. In this approach, a few of the most general and most specific concepts were defined first. They were then linked with some middle-level concepts. For instance, the ‘crane’ can be a general concept, and the specific geometry of space requirement for a crane operation can be a specific concept. They can be connected using intermediate classes, such as ‘geometry.’ This process is repeated multiple times till all the terms are designated in an adequate class hierarchy (Noy & McGuinness, 2001).

Figure 1 shows the class hierarchy of CSRO as shown in the Protégé interface. It consists of four classes, i.e., *Crane*, *CraneComponent*, *Geometry*, and *Solid*. The *Crane* class has *CrawlerCrane* as a subclass, which can be extended to other types of cranes. The *CraneComponent* class has different significant components of the crane as subclasses. The *Geometry* and *Solid* classes are not explicitly created in CSRO. The *Geometry* class is imported from Simple Features ontology (https://opengeospatial.github.io/ogc-geosparql/geosparql11/sf_geometries.ttl), and the *Solid* class is imported from Geometry (http://rdf.bg/geometry.ttl#) ontology for specific purposes.



Class hierarchy: owl:Thing

- owl:Thing
  - Crane
    - CrawlerCrane
  - CraneComponent
    - AuxiliaryCounterweights
    - Boom
    - BoomMast
    - CrawlerBase
    - Gantry
    - HoistRope
    - LiftingAssembly
    - LiftingHook
    - LowerRotatingBody
    - ObjectLifted
    - Outriggers
    - RingSystem
    - RopesAndPendants
  - Geometry
    - Point
    - Surface
      - PolyhedralSurface
  - Solid
    - Cylinder
    - HollowCylinder
    - InvertedCone

Figure 1:Class hierarchy of CSRO

The space occupied by the crane to be placed at a particular location was represented in CSRO using 3D bounding boxes covering its components. Despite not capturing accurate geometry, bounding boxes offer an approximate representation that can be used for space constraint checking (Chen et al., 2017). To represent such bounding boxes on the semantic web, the *PolyhedralSurface* sub-subclass, which is a subclass of the *Surface* class, was used.

The crane operation also involves the rotation of its components. For instance, The lower rotating body of the crane can rotate around the center of rotation while lifting the load (Lei et al., 2013). The Point subclass was imported from the simple features ontology to consider such a center of rotation. The space required for such rotation was represented in CSRO in the form of a cylinder with its radius and height depending upon the dimensions of the crane component. To consider this, the *Cylinder* subclass of the *Solid* class was imported from the Geometry ontology. Similarly, the crane boom also rotates while transferring the lifted object. The space required for such boom rotation is governed by the maximum and minimum possible radius of operation of the crane (Aghajamali et al., 2023; Lei et al., 2013). As the crane boom is inclined and rotates about a center point, the space required for such rotation can be roughly considered as a cone, as shown in Figure 2a. Therefore, the *InvertedCone* subclass was created as the subclass of the *Solid* class. As the boom rotates, the attached lifting assembly and the lifted load also rotate. The space required for such rotation takes the form of a hollow cylinder, as shown in Figure 2b. Therefore, the *HollowCylinder* subclass was introduced in the *Solid* class.

STEP 5: DEFINE THE PROPERTIES OF CLASSES – SLOTS

Object properties connect the classes, and datatype properties relate classes to specific values. (Noy & McGuinness, 2001). The object and datatype properties in this study were defined based on the different types of class-to-class and class-to-datatype relationships needed to represent the space requirement of the crane. A brief description of the object and datatype properties used in CSRO is given in Table 1 and Table 2.

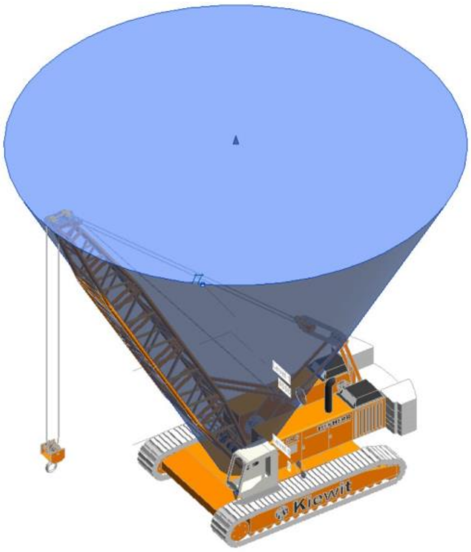


Figure 2a: Space requirement for the boom rotation

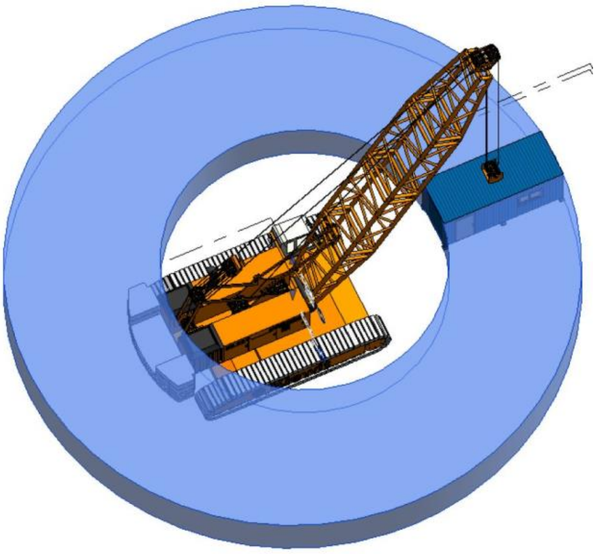


Figure 2b: Space requirement for rotation of the lifted object

Table 1: Object properties used in CSRO

Property names	Purpose	Domain	Range
hasComponent	Connecting a crawler crane class to its components	CrawlerCrane	Crane- -Component
hasBoundingBox	Connecting crane components to their bounding box representations in the form of polyhedral surfaces	Crane- -Component	Polyhedral- -Surface
hasCylindricalRotation- -Space	Connecting relevant crane components to the cylinder geometry representing their rotational space requirement	AuxiliaryCounter- -weights, LowerRotating- -Body	Cylinder
hasMaximumConical- -Space, hasMinimumConical- -Space	Connecting the crane boom to the inverted cone geometry representing its rotational space requirement at the maximum and minimum boom radius	Boom	Inverted- -Cone
hasMaximumHollow- -CylindricalSpace, hasMinimumHollow- -CylindricalSpace	Connecting relevant crane components to the hollow cylinder geometry representing their rotational space requirement at the maximum and minimum boom radius	LiftingAssembly, HoistRope, LiftingHook, ObjectLifted	Hollow- -Cylinder
hasVerticalMotion- -Space	Connecting relevant crane components to the cylinder geometry representing their vertical motion space requirement	LiftingAssembly, LiftingHook, ObjectLifted	Cylinder
hasCenterofRotation	Connecting geometries such as Cylinder and InvertedCone to their center of rotation.	Cylinder, HollowCylinder, InvertedCone	Point

Table 2: Datatype properties used in CSRO

Property names	Purpose	Domain	Range
hasModelNumber	Mentioning crane’s model name and number using string datatype	CrawlerCrane	xsd:string
asWKT	Describing the geometries such as polyhedral surfaces and points using WKT literals	Geometry	WKT Literal
Innerradius, outerradius	Providing the float values of the inner and outer radius of the hollow cylinder	HollowCylinder	xsd:float
height	Providing the float values of the height of the hollow inverted cone	InvertedCone	xsd:float
length	Providing the float values of the length of the cylinder and hollow cylinder	Cylinder, HollowCylinder	xsd:float
radius	Providing the float values of the radius of the cylinder and inverted cone	Cylinder, InvertedCone	xsd:float

STEP 6: DEFINE THE FACETS OF THE SLOTS

The defined properties were connected to their domain and range. Domain and range are the classes/datatypes to which a property's subject and object belong in a linked data representation. Table 1 and Table 2 provide concise details about the domain and range of the properties in CSRO. Figure 3 depicts CSRO, including all its classes and properties.

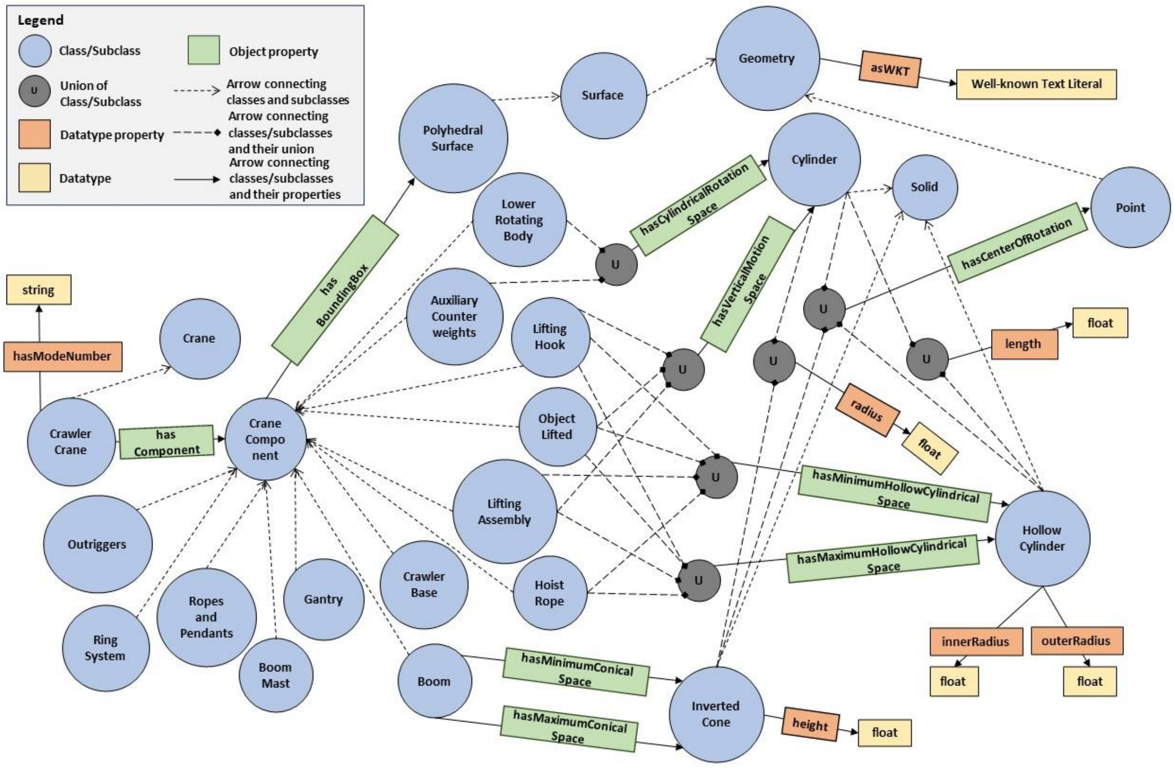


Figure 3: Crane Space Representation Ontology

STEP 7: CREATE INSTANCES

At this stage, individual instances corresponding to the classes and properties are defined, and the associated properties are assigned the values according to the instance. For demonstration, a Revit family of a crawler crane was imported into a Revit model, and the values of the properties were assigned accordingly. Figure 4a shows the crane with a bounding box around its boom. The coordinates of the corner of the bounding box are identified using the spot coordinates feature of Revit. The representation of this bounding box based on CSRO ontology is depicted in Figure 4b. Similarly, other space requirements can be instantiated.

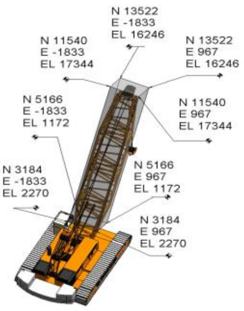
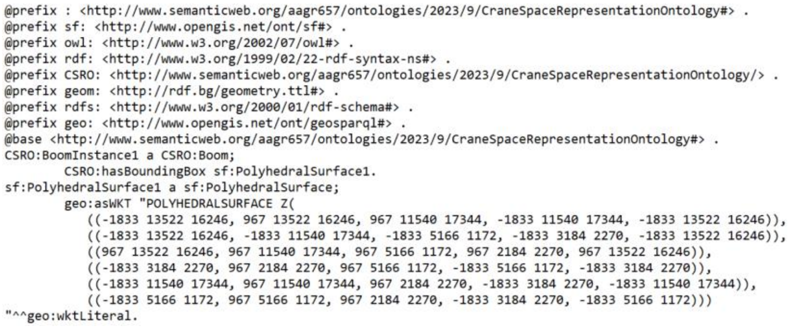


Figure 4a: Crane boom with bounding box

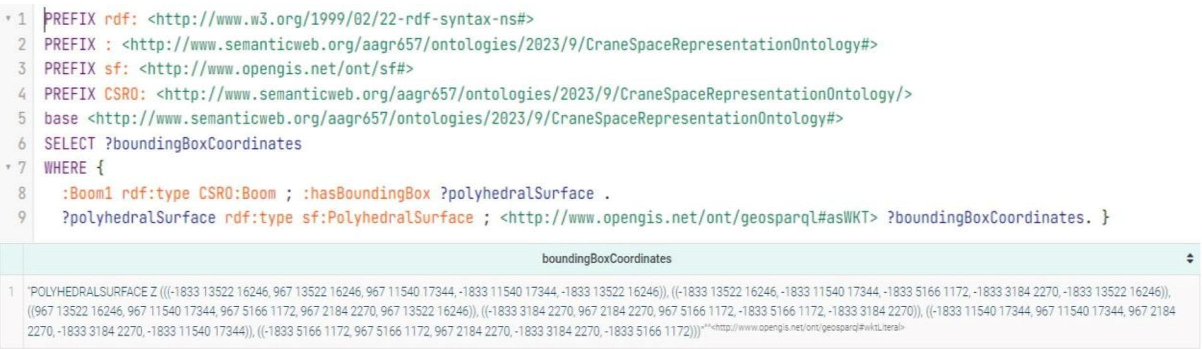


```
@prefix : <http://www.semanticweb.org/aagr657/ontologies/2023/9/CraneSpaceRepresentationOntology#> .
@prefix sf: <http://www.opengis.net/ont/sf#> .
@prefix owl: <http://www.w3.org/2002/07/owl#> .
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix CSRO: <http://www.semanticweb.org/aagr657/ontologies/2023/9/CraneSpaceRepresentationOntology/> .
@prefix geom: <http://rdf.bg/geometry.ttl#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix geo: <http://www.opengis.net/ont/geosparql#> .
@base <http://www.semanticweb.org/aagr657/ontologies/2023/9/CraneSpaceRepresentationOntology#> .
CSRO:BoomInstance1 a CSRO:Boom;
        CSRO:hasBoundingBox sf:PolyhedralSurface1.
sf:PolyhedralSurface1 a sf:PolyhedralSurface;
        geo:asWKT "POLYHEDRALSURFACE Z(
           ((-1833 13522 16246, 967 13522 16246, 967 11540 17344, -1833 11540 17344, -1833 13522 16246)),
           ((-1833 13522 16246, -1833 11540 17344, -1833 5166 1172, -1833 3184 2270, -1833 13522 16246)),
           ((967 13522 16246, 967 11540 17344, 967 5166 1172, 967 2184 2270, 967 13522 16246)),
           ((-1833 3184 2270, 967 2184 2270, 967 5166 1172, -1833 5166 1172, -1833 3184 2270)),
           ((-1833 11540 17344, 967 11540 17344, 967 2184 2270, -1833 3184 2270, -1833 11540 17344)),
           ((-1833 5166 1172, 967 5166 1172, 967 2184 2270, -1833 3184 2270, -1833 5166 1172)))
"^^geo:wktLiteral.
```

Figure 4b: Polyhedral surface representation of the bounding box

ONTOLOGY EVALUATION

The ontology evaluation ensures clarity, completeness, consistency, and fitness for the purpose of the developed ontology (Zheng et al., 2020). Several methods for ontology evaluation are available, including task-based evaluation, gold standard evaluation, and automated consistency checking, among others (Zheng et al., 2021). As CSRO was developed for the specific task of representing the space requirement of crane operation, automated consistency checking and task-based evaluation were used for its evaluation. These methods have also been used to evaluate other task-specific ontologies (Zheng et al., 2020). To check the consistency, this study utilizes Protégé's HermiT reasoner due to its faster speed and memory efficiency compared to other reasoners such as Pellet (Glimm et al., 2014). On running the reasoner, it showed no error, ensuring the consistency of the ontology. SPARQL queries were developed for task-based evaluation to check if the ontology-based knowledge base can answer the developed competency questions. The knowledge base was developed based on the crane family imported in Revit. An open-source tool named GraphDB was used to run the queries. The total space required to position a crane at a particular location can be expressed as the bounding boxes covering its components. Figure 5 shows the SPARQL query for extracting the bounding box of the crane boom. The query successfully fetched the bounding box in the form of the polyhedral surface, as shown in Figure 5. Similarly, the queries to address other competency questions were written. The queries could successfully extract the required information from the knowledge base and answer all the competency questions.



```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX : <http://www.semanticweb.org/aagr657/ontologies/2023/9/CraneSpaceRepresentationOntology#>
PREFIX sf: <http://www.opengis.net/ont/sf#>
PREFIX CSRO: <http://www.semanticweb.org/aagr657/ontologies/2023/9/CraneSpaceRepresentationOntology/>
base <http://www.semanticweb.org/aagr657/ontologies/2023/9/CraneSpaceRepresentationOntology#>
SELECT ?boundingBoxCoordinates
WHERE {
  :Boom1 rdf:type CSRO:Boom ; :hasBoundingBox ?polyhedralSurface .
  ?polyhedralSurface rdf:type sf:PolyhedralSurface ; <http://www.opengis.net/ont/geosparql#asWKT> ?boundingBoxCoordinates. }
```

	boundingBoxCoordinates
1	"POLYHEDRALSURFACE Z (((-1833 13522 16246, 967 13522 16246, 967 11540 17344, -1833 11540 17344, -1833 13522 16246)), ((-1833 13522 16246, -1833 11540 17344, -1833 5166 1172, -1833 3184 2270, -1833 13522 16246)), ((967 13522 16246, 967 11540 17344, 967 5166 1172, 967 2184 2270, 967 13522 16246)), ((-1833 3184 2270, 967 2184 2270, 967 5166 1172, -1833 5166 1172, -1833 3184 2270)), ((-1833 11540 17344, 967 11540 17344, 967 2184 2270, -1833 3184 2270, -1833 11540 17344)), ((-1833 5166 1172, 967 5166 1172, 967 2184 2270, -1833 3184 2270, -1833 5166 1172)))"^^<http://www.opengis.net/ont/geosparql#wktLiteral>

Figure 5:SPARQL query and results related to CQ1

CONCLUSION AND FUTURE RESEARCH

In LAP, checking space constraints related to crane usage for crane-dependent operations is critical for developing quality assignments for trade crews and ensuring a reliable workflow. Given the complexity and dynamicity of construction projects, frequent constraint checks and adjustments to lookahead schedules are necessary. Further, the information required for constraint-checking remains in disparate, often non-interoperable databases. Therefore, conventionally used manual constraint-checking is tedious and error-prone, and most existing automated constraint-checking methods are not applicable in LAP. Consequently, LAP suffers from poor constraint-checking. Linked data based constraint-checking provides an opportunity to address these gaps. However, adequate space constraint-checking for crane-dependent operations using linked data is still lacking due to the unavailability of an ontology that can represent the space required for crane operation on the semantic web. Improper space constraint checking can result in time-space conflicts and unsafe conditions on the site, contributing to non-value-adding activities such as resource wastage. To address this gap, this paper developed Crane Space Representation Ontology (CSRO) for mobile crawler cranes with a lattice boom. CSRO considers the different elements of the space required for crane operation, such as the space needed to place the crane at a particular location and to rotate the crane's various components. The representation of such space requirements is done through different geometries such as cylinder, cone, and bounding box. The ontology is evaluated using automated consistency checking and a task-based evaluation approach. The evaluation results confirm the consistency of the ontology and its ability to answer intended competency questions.

This study contributes to research on leveraging technology for lean construction implementation by introducing a novel ontology to facilitate automated constraint checking in LAP. The CSRO can be semantically linked with the crane-dependent operations in lookahead schedules, as-built data, and other relevant information containers to perform automated linked data based checking of space constraints associated with operations involving crane usage. This provides two-fold benefits from a lean perspective. First, such space constraint checking can be used to develop constraint-free lookahead schedules based on the latest information from heterogeneous databases, improving workflow reliability and reducing non-value-adding activities on the site. Second, automation can reduce time, human effort, and error likelihood in the space constraint checking process, contributing toward minimizing rework and resource wastage in LAP and reducing potential non-value-adding activities on site due to errors in LAP.

In the future, CSRO should be extended to represent space required for other types of cranes as well, such as crawler cranes with luffing jib, cranes with telescopic boom, and tower cranes, among others. Future studies should extend CSRO to consider such additional operations such as walking, simultaneous slewing and lifting. Currently, significant manual effort is needed to process the heterogeneous information containers and ensure that the right information is expressed by the concepts of CSRO. Similar concepts might be represented by different terms in different databases, which might create ambiguities during representing data using CSRO. Future research should aim to develop automated tools for semantically annotating information containers to extract relevant data needed for crane space representation using CSRO. In addition, efforts should be made toward unification of semantic standards and development of equivalent relationships between the concepts. Finally, in the future, the authors will focus on utilizing CSRO to perform space constraint checking in lookahead schedules.

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