An Extensible Construction Ontology to Guide Job-Site Sensing and Support Information Management

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Abstract

Real-time sensing data and continuously updated project documents pose challenges to project managers who need to analyze these data and documents to derive meaningful information necessary for decision-making. To collect and incorporate heterogeneous data both from offsite and onsite sources, the authors: (1) developed a construction tasks, resources, and techniques integrated (ConTaRTI) ontology to classify construction site information that is extensible; and (2) encoded recommendations regarding sensing technique selection into the proposed ConTaRTI ontology, which aims to help collect data for meeting real-time construction information needs. The proposed ConTaRTI ontology offers a novel way to classify construction information that needs to be collected, measured, and detected on the site, given its real-time decision contexts. The ConTaRTI ontology also helps provide sensing technique recommendations to guide the selection of methods and tools for the data collection on specific construction tasks and resources. Therefore, the ontology enables a new method for construction information management by linking construction site information with suitable data collection methods. In addition, the extensibility and flexibility of the proposed ontological model opens a new door to organizing and integrating specific information needs with its collection/process methods to support information management. The quantitative and qualitative evaluation results indicate that the developed ontology can recommend sensing techniques that effectively support field data collection and information management.

Keywords –

Construction Ontology; Sensing Techniques; Job Site Data; Automation; Information Management

1 Introduction

Construction site contains various types of data represented in different ways, including labor-related, equipment-related, and material-related information coded in textual [1] and graphic [2] formats, among others. Successful collection and use of such data plays an essential role in supporting construction information management, such as information transfer between different stakeholders. The heterogeneous data for construction management can be from offsite (e.g., construction plans and documents) and onsite (e.g., execution of tasks) sources, covering labor, materials, equipment, etc. [3] They provide helpful information to support other construction applications, such as construction monitoring [4]. Therefore, leveraging different types of data efficiently and accurately is an essential research topic of great interest to support various construction applications.

The research presented in this paper examines a new construction tasks, resources, and techniques integrated (ConTaRTI) ontology that is extensible. This ontology classifies construction site information based on their nature and the data collection requirements, then provides encoded sensing technique recommendations regarding data collection methods for specific construction site information. The proposed ConTaRTI ontology was developed in Web Ontology Language (OWL) and further implemented with an app that allows users to explore: (1) construction tasks (i.e., construction activities) and resources (i.e., labor, material, and equipment) on the construction site; (2) sensing technique recommendations regarding data collection methods suitable for specific tasks and resources; and (3) relationships between (1) and (2) with corresponding literature references. This work forms the basis for an ontology-based information management framework that can integrate textual procedural information extraction (IE), sensing technique recommendation and selection, and information analysis application into one framework to support construction information management.

2 Background

Sensing techniques are essential in transferring traditional manual data collection to automated ones to support business operations, such as site conditions monitoring, equipment, and material management, worker safety, and facility management, among others [5]. With the advancement of sensing techniques, various construction management applications (e.g., construction monitoring and risk analysis) and duties (e.g., construction resources tracking and allocation) can be supported by the increasingly available sensing data. With their various applications and performances in precision, cost, bandwidth, and measurement range, different sensing techniques have distinguished purposes, advantages, and limitations [6]. Accordingly, it is necessary to leverage different sensing techniques to collect the construction site data. For example, photogrammetry can be used to obtain distance information [7], global positioning systems (GPS) can be used to collect information of moving objects and changes in large facilities [8], and three-dimensional (3D) imaging systems (e.g., laser scanners) can be used to capture detailed spatial information about construction workspaces [9].

In the construction domain, the state-of-the-art computer vision applications support object detection, image classification, object segmentation, and pose estimation [10], among others. In addition to imaging sensors, many other sensors have found applications in the construction domain. For example, wearable sensors [e.g., inertial measurement unit (IMU), electromyography (EMG), accelerometer, and gyroscope sensors] can detect movements. Versatile and portable wearable sensors have shown great potential for construction activity recognition [11]. Radio-frequency identification (RFID) and radio-frequency tags can track and locate materials and components on the construction site actively and accurately to better assist construction tasks on the job site (e.g., material tracking) [12]. Augmented reality (AR) and virtual reality (VR) can support various construction management applications, such as construction project planning and scheduling, progress monitoring, workers' training, and site management and visualizations [13-15].

With the technological development and innovation in the construction domain, operations at construction job sites have become increasingly complex and dynamic, posing challenges in managing resources (e.g., labor, materials, and equipment). Sensors can monitor a variety of physical objects and parameters in the field. Therefore, using sensors on the construction job site has become popular, which can help stakeholders in supporting their decision-making with needed data and information.

Despite the wide variety of sensors and corresponding data analytic methods, no "ideal" sensing technique can serve as a comprehensive solution to universally support all construction applications and management issues. For instance, the widely used computer vision technique still has limitations due to limited annotated datasets and objects with special appearances (e.g., shiny surfaces), causing detection errors [16]. Consequently, effectively selecting and leveraging a target sensing technique to support a specific construction task or application is an important need in the AEC domain. To address this, the authors proposed an extensible construction ontology by considering both construction site information and sensing techniques to guide job-site sensor planning and construction information management.

The main challenge in construction information management is the presence of various data types, including structured data files, semi-structured data files, unstructured text data files, to name a few [17]. Therefore, the effective selection and use of different information for various construction field applications (e.g., process control and manufacturing, detecting and preventing risks) are imperative. The augmentation of sensor networks with sensor information management methods can help collect and process data for efficient and effective data-driven decision-making on construction sites [18].

To summarize, by adopting, improving, and adjusting new sensing technologies on construction sites, construction information management can be supported and facilitated by leveraging and processing heterogeneous data collected by these emerging sensing techniques. In this paper, the authors proposed an extensible construction ontology to help efficiently and accurately provide sensing technique recommendations for guiding construction site data collection, given the characteristics of field applications.

3 Ontological Model Development

Ontology aims to simplify the point of view to represent something for a specific purpose, which is a straightforward specification of an abstract [19]. An ontology defines a list of terms (i.e., concepts), the relationships among them, and the axioms (i.e., definitions of concepts and relationships, and their constraints) coded in hierarchal structures [20]. Concepts define the "things' (e.g., entities and categories) either abstractly or concretely in the domain of interest. An entity represents an action, actor, product, resource, project, or mechanism [20]. An entity has an attribute, and a modality. Concepts in the ontology are associated with three relationships: is-a, part-of, and cross-concept relationships. Is-a relationship is also known as subsumption relationship, representing the specialization of a super-concept into a specialized sub-concept. The part-of relationship captures the decomposition of a concept into corresponding comprised parts. The cross-concept relationship represents non-hierarchical semantic links between concepts, demonstrating the reason for assigning each link. One important nature of an ontology is in its reusability, so that “reinventing the wheel” can be avoided [20]. Because parts and pieces of any existing related ontology can be reused, it is therefore feasible and necessary to target the development of one ontology for a specific domain and purpose. There was no lack of ontology development for the construction domain, examples include ontology for construction safety knowledge management [21], ontology for sustainable construction [22], among others. However, as far as the authors are concerned, there is a need of an ontology for linking construction site data to their suitable sensing techniques.

Five main steps form the general procedure of ontology development following the top-down approach to ensure a clear structure from the beginning, including (1) defining the purpose and scope of the ontology; (2) building classes and class hierarchy in the ontology; (3) defining relationships between classes; (4) implementing ontology; and (5) evaluating ontology [23]. In this research, the authors developed an extensible ConTaRTI ontology to demonstrate the connections between construction site information and their corresponding sensing techniques, for targeted job-site data collection with appropriate sensing techniques. One main hypothesis is that all construction data and sensing techniques of interest can be found in literature. A computational reasoning framework powered by ConTaRTI is also proposed to provide sensing technique recommendations and further support construction information management. This purpose dictates the represented information in the ontology, including construction site information and sensing techniques classified hierarchically. In addition, the sensing technique recommendations for different construction site information are provided with their literature references. Figure 1 illustrates the ConTaRTI ontology development procedure.

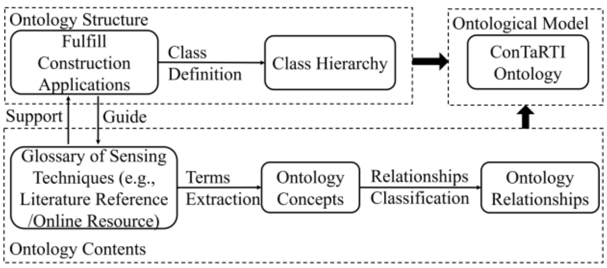


Figure 1. ConTaRTI Ontology Development Process

The purpose of the ConTaRTI ontology is to identify sensing techniques that fulfill given construction applications and site conditions (Figure 1). This purpose dictates the structure of the proposed ontology and helps define the classes and class hierarchy. The authors conducted a literature review regarding construction site information and sensing techniques for data collection, which helped define the concepts and their relationships. The proposed ConTaRTI ontology is encoded in the Protégé (version 5.5.0) using OWL. Protégé is an open-source ontology development editor for developing knowledge-based intelligent systems [24]. The ontology development process involves iterative evaluations and improvements of the ConTaRTI ontology from quantitative and qualitative perspectives.

Associating construction tasks and resources with their corresponding sensing techniques for data collection is the core theme for the ConTaRTI ontology development. Therefore, the ConTaRTI ontology could guide engineers, managers and other site personnel in collecting job-site data and further support construction information management. It is not expected/intended to be the “only” information management model for guiding the job site sensing data collection because “there is no “perfect” ontology and no “optimum” classifications or concept hierarchies” [20]. The authors design this extensible ontology with flexibility and extensibility in mind while keeping the fundamental requirements of connecting information needs and attributes of sensing techniques. Thus, developing this extensible ontology supports the intelligent provision of sensing technique recommendations for collecting construction site information.

4 Ontology Implementation, Experimental Results and Analysis

The ConTaRTI ontology covers construction site information that affects the sensing techniques to select from (for site data collection), including (1) resources class: labor, materials, and equipment; and (2) tasks class: labor-based activities, equipment-based activities, labor, and equipment-based activities, labor and material-based activities, labor and equipment and material-based activities, and equipment and material-based activities. The corresponding sensing techniques for each construction resource and task were incorporated into the extensible ontology and assigned to the specific resource and/or task. The information mentioned above was encoded in the proposed ConTaRTI ontology using Web Ontology Language (OWL) in Protégé (version 5.5.0). Then the encoded ontology was implemented with a user-friendly interface. Python programming language (Python 3.5.3) was used for implementing the developed ontology interface.

The method for implementing the ConTaRTI ontology includes five steps. Step 1: Construction Tasks and Resources Information Development – This step classifies construction site information into different categories to support ontology development. Step 2: Construction Sensing Techniques Information Development – This step lists the sensing techniques used to collect different categories of construction site information as identified in Step 1. The selected sensing techniques were identified based on academic literature such as those from Scopus, Google Scholar, and ASCE library, which provides evidence to support further sensing technique recommendation provisions in Step 3. Step 3: Technical Recommendation Regarding Sensing Technique Selection – This step connects the selected information in the ontology in Step 1 and their corresponding sensing technique information in Step 2 to guide sensing technique selection and uses. Step 4: Ontology Integration – This step incorporates the defined construction site information in Step 1, sensing techniques in Step 2, and their relationships in Step 3, and implements them into an ontology-based user-friendly app for guiding job-site data collection. The developed app makes job-site sensing guidance one step closer to full automation, to support construction information management and decision-making. In the app, the corresponding sensing technique(s) for the specific type of construction site information will be provided based on the user selection of specific tasks (i.e., construction activity) or resources (i.e., labor, material, and equipment) in the ConTaRTI ontology. Step 5: Ontology Evaluation – This step evaluates the developed ontology from quantitative and qualitative perspectives. The evaluation results will inform the improvements of the ontology.

4.1 Step 1: Construction Tasks and Resources Information Development

The developed ConTaRTI ontology covers three main areas: (1) construction site information, (2) sensing techniques, and (3) their relationships. Construction site information includes construction tasks and resources. Furthermore, construction resources include labor (e.g., construction worker), equipment (e.g., hydraulic excavator), and materials (e.g., concrete). In addition, construction tasks contain all the resource-related activities, including labor-based activities (e.g., walking), equipment-based activities (e.g., tower crane boom's movement), labor and equipment-based activities (e.g., welding), labor and material-based activities (e.g., inspection of windows/doors), labor and equipment and material-based activities (e.g., pouring concrete from concrete truck), and equipment and material-based activities (e.g., tower crane loading concrete). Our hypothesis was construction tasks that need such explicit resources are the ones that need sensing for data collection. The ConTaRTI ontology covers various information on the construction job sites that need sensing techniques to capture.

4.2 Step 2: Construction Sensing Techniques Information Development

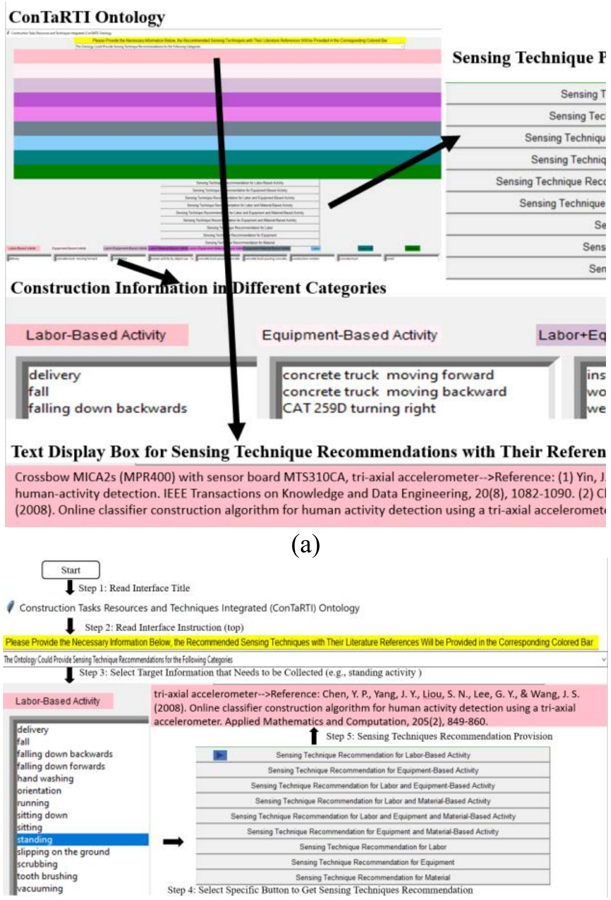
To facilitate data collection on construction sites, the sensing techniques are incorporated into the ConTaRTI ontology to fill the need. In the ConTaRTI ontology, the construction tasks and resources with corresponding sensing techniques (for data collection) follow one-to-one or one-to-many relationships. All the sensing techniques in the ConTaRTI ontology were selected based on and backed up by literature. Literature provides both the data source and reference information, demonstrating the relationships between sensing techniques and corresponding construction site information they can be used to collect data for.

4.3 Step 3: Technical Recommendation Regarding Sensing Technique Selection

In this step, the relationships between the construction tasks and resource information identified in Step 1 and the corresponding types of sensing techniques identified in Step 2 are defined and encoded into the ontology. For example, the recommendation of the Crossbow MICA2s with sensor board MTS310CA and tri-axial accelerometer will be provided based on the ConTaRTI ontology to collect data for the walking activity which is a labor-based activity [25]. Linking the construction tasks and resources with their data collection sensing techniques integrates the two parts of the ConTaRTI ontology.

4.4 Step 4: Ontology Integration

In this step, the ConTaRTI ontology is encoded in OWL using Protégé. An ontology-based app is developed to support the use of the ontology in a user-friendly manner (Figure 2). There are nine main categories regarding sensing technique recommendations (Figure 2(b)), with 55 classes and 63 properties (relations). Users could select specific terms of construction tasks or resources in different categories when running the app by activating the corresponding functions. The app will then demonstrate the sensing technique recommendations with their literature references in the text display box in color coding. Figure 2(a) illustrates the ontology-based app with zoomed-in looks, Figure 2(b) demonstrates the steps of using the developed interface. In Figure 2(a), the sensing technique Crossbow MICA2s with sensor board MTS310CA and tri-axial accelerometer with literature references are provided for walking in the labor-based activity category (pink color coding).



(a)

(b)

Figure 2. (a) ConTaRTI Ontology-Based App; (b) Ontology-based Interface Explanation with an Example

4.5 Step 5: Ontology Evaluation

Ontology evaluation is critical for ensuring reliable information management in multiple domains. Hlomani and Stacey pointed out that quality and correctness are two critical metrics for evaluating ontologies. Several specific criteria of the above-mentioned metrics include conciseness, accuracy, adaptability, completeness, computational efficiency, clarity, and consistency [26].

Raad and Cruz [27] identified four categories for methods to evaluate an ontology, including "gold standard-based, corpus-based, task-based and criteria-based" methods, respectively. Gold standard-based methods are the most straightforward and widely used type. When using the gold standard-based methods, a newly developed ontology is compared against a reference ontology. Corpus-based methods are used to mainly evaluate the coverage of a newly developed ontology for a specific domain in a data-driven manner. When using the corpus-based methods, the newly developed ontology is compared against a domain-specific text corpus. Task-based methods are used to mainly assess the improvement to a certain task when using an ontology, which therefore only evaluates the ontology's performance for a specific task without considering its structural characteristics or broader use. Task-based methods can also be used to evaluate the adaptability of an ontology to a specific task. Based on Raad and Cruz [27], "adaptability measures how far the ontology anticipates its uses." Criteria-based methods are used to assess the adherence of a newly developed ontology to a specific criterion. Table 1 summarizes different criteria for each ontology evaluation method, in which three levels (i.e., high, medium, and low) are assigned to the corresponding criterion in different methods [27].

Table 1 Overview of ontology evaluation methods [27]

	Gold standard-based methods	Corpus-based methods
Accuracy	High	High
Completeness	High	High
Conciseness	High	High
Adaptability	Medium	Low
Clarity	Medium	Medium
Computational efficiency	Low	Low
Consistency	Medium	Medium

Table 1 (continued)

	Task-based methods	Criteria-based methods
Accuracy	Low	Medium
Completeness	Medium	Low
Conciseness	Medium	Medium
Adaptability	High	Medium
Clarity	Medium	High
Computational efficiency	High	High
Consistency	High	High

4.6 Experimental Test

An experiment was conducted to evaluate the developed ConTaRTI ontology using the task-based method because the nature of our developed ontology is serving construction tasks. The proposed ontology was implemented with an interface to perform the assigned task. Accordingly, a given task was assigned to use the ontology to recommend sensing techniques for specific construction site information (i.e., construction resources and tasks) in terms of data collection in the given scenario. Figure 3 demonstrates an example procedure of using the ConTaRTI ontology. Firstly, a user could select specific construction resources and tasks in different categories (e.g., labor-based activity). Then, the user activates the corresponding function (e.g., Sensing Technique Recommendation for Labor-Based Activity). The sensing technique selection recommendation with its literature reference will then be provided in a text display box with the same color coding as the name of the selected category (e.g., pink for Labor-Based Activity).

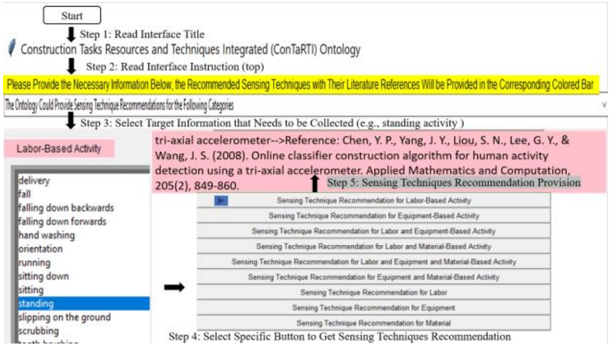


Figure 3. Ontology-based App Explanation with an Example

4.7 Evaluation

The proposed ontology was evaluated in providing recommendations regarding appropriate sensing technique selection for supporting the collection of specific construction site information in a given scenario. In this research, three criteria are considered for ontology evaluation [23]: adaptability, computational efficiency, and consistency, which represent the criteria well covered by task-based ontology evaluation methods (Table 1).

Computational efficiency and consistency were used for quantitative analysis, and adaptability was used for qualitative analysis. Based on Raad and Cruz [27], "Computational efficiency measures the ability of the used tools to work with the ontology." Accordingly, in this research, the computational efficiency demonstrates the time consumption with and without the use of the ConTaRTI ontology, which is reflected/implemented with a user-friendly app, to obtain sensing technique selection recommendations. With the implemented ConTaRTI ontology, users only needed to activate the corresponding function to get sensing technique recommendations backed by literature references. On the contrary, without using the implemented ConTaRTI ontology, the users needed to either browse online or check publications/websites or other resources to get the sensing technique recommendations, which is time-consuming and labor-intensive. Three independent researchers conducted the evaluation of computational efficiency. They randomly tested twenty-five construction tasks and resources in the ConTaRTI ontology, then calculated the time spent on each of the twenty-five selections to get the average time consumption.

The average time consumption when using the ConTaRTI ontology to get sensing technique recommendations was 4.664 seconds (standard deviation = 1.36 seconds). Meanwhile, the average time consumption without using the ConTaRTI ontology was 5.489 minutes (standard deviation = 73.45 seconds). Figure 4 shows the line chart of the computational efficiency testing results. In Figure 4, the x-axis represents the number of trials. The y-axis demonstrates the time consumption (unit: second). Accordingly, the time consumption using ConTaRTI ontology (i.e., blue line) is much less than without using the ontology (i.e., red line). In addition, the time consumption with the use of the ontology is much more stable than without using it, as reflected in the computational efficiency testing results (Table 2). It shows that the time consumption efficiency improved 98.58% when using the ConTaRTI Ontology. It demonstrates that the proposed ConTaRTI ontology is promising to provide efficiency in sensing technique recommendation/selection for construction site data collection.

Table 2 An overview of ontology evaluation methods

Method	Without the use of the ConTaRTI ontology	With the use of the ConTaRTI ontology	Evaluation result
Computational efficiency	On average 5.489 minutes	On average 4.664 seconds	98.58% improvement

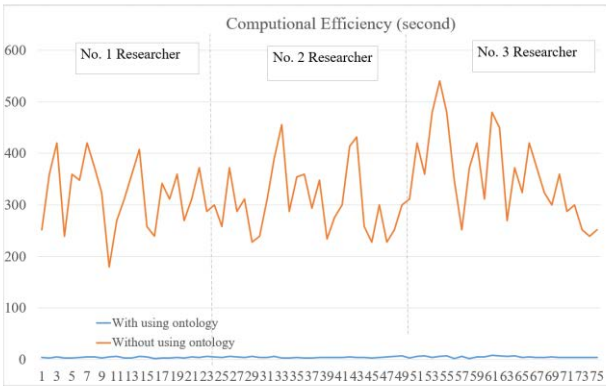


Figure 4. Line Chart of Computational Efficiency Testing Results

Adaptability illustrates how far the ConTaRTI ontology is anticipated for different tasks/applications/scenarios [27]. The authors considered other potential applications of the ConTaRTI ontology in several broad areas (e.g., educational, commercial, and research areas), such as (1) illustrating sensing technique recommendations for specific construction site information, which can be used as an educational tool to motivate students' learning in advanced construction technology; (2) supporting commodity purchase decision for construction contractors in selecting the most suitable sensor for specific data collection needs and budget available; and (3) providing research tool guidance for target construction site-related research in an efficient way, in areas such as safety management, construction worker monitoring, and smart construction, among others. In addition, the developed ontology provides the conceptual foundation for anticipated construction site management tasks. The extensible ontology was implemented in a user-friendly app, in which the two types of information (i.e., construction site information and sensing techniques) and their relationships were encoded into the ontology. This can be put to use directly, or the contents can be easily adjusted and extended to other applications, such as in providing recommendations regarding project delivery methods based on different types of projects and organizational structures, in which the only adjustment needed is in the relevant concepts and relationships to fulfill the intended usage. For example, within the same structure of the ConTaRTI ontology, the two main parts (i.e., construction information and sensing techniques) could be replaced with different types of project and organizational structures, and project delivery methods, respectively. Then the relationships between them could be assigned based on literature references accordingly. Therefore, the ConTaRTI ontology provides a structural foundation for documenting mapping relationships to support many tasks/applications.

Consistency is an evaluation metric to check if "the ontology does not include or allow for any contradictions" [27]. In this paper, an open-source reasoner named HermiT [28] was used to evaluate the consistency of the proposed ontology. HermiT is an OWL ontology reasoner, which determines if "the ontology is consistent, and identifies subsumption relationships between classes" [29]. In this research, the ontology was imported into Protégé, then HermiT reasoner was executed to evaluate the ontology, in which the majority of the ontology contents were found to be consistent (95%). After minor revisions (e.g., adjustment of *DisjointWith* relationships between different categories), the ontology was found to be completely consistent (100%).

In summary, based on the evaluation results in adaptability, computational efficiency, and consistency, the ConTaRTI ontology: (1) could provide the conceptual and structural foundations for anticipated construction tasks, (2) achieved a 98.58% time efficiency improvement compared with the manual approach, and (3) achieved high/complete consistency. These results show that the developed ConTaRTI ontology is promising in providing sensing technique selection recommendations to different construction resources and tasks and other construction applications. It is expected to support construction information management.

5 Conclusion and Future Work

This paper presented an extensible construction tasks, resources, and techniques integrated (ConTaRTI) ontology by encoding construction site information, its corresponding sensing technique for data collection, and the relationships between them. It covers the major types of information on the construction site that may need support by sensing techniques in data collection. In the ConTaRTI ontology, both the recommended sensing techniques and their corresponding literature references are provided to demonstrate the sensing technique selection recommendations, which can support decision-making in the construction domain efficiently and accurately. The developed ConTaRTI ontology was quantitatively and qualitatively evaluated using a task-based approach to assess its adaptability, computational efficiency, and consistency. It demonstrates that the developed ConTaRTI ontology is extensible and flexible, and could be implemented in the construction domain to: (1) help provide sensing technique selection recommendations regarding data collection methods for specific construction resources and tasks, and (2) support other tasks in construction information management. In their future work, the authors plan to extend the categories of construction information and sensing technologies in the proposed ontology to cover a broader scope for use in different types of construction projects.

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