Retraction Notice

The Editor-in-Chief and the publisher have retracted this article, which was submitted as part of a guest-edited special section. An investigation uncovered evidence of systematic manipulation of the publication process, including compromised peer review. The Editor and publisher no longer have confidence in the results and conclusions of the article.

MNA and AS agreed with retraction.

Systematic review on ontology applications in virtual reality training domain: design components, roles, and research directions

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Abstract. Even though ontology and virtual reality training (VRT) are subjects that have been explored in various areas over the years, there is an absence of a systematic approach that gives an overview on how both have been utilized together. We aim to explore how ontologies have been applied in VRT technology in recent times. Therefore, the systematic literature review methodology was carried out to collect studies between 2014 and 2021 from various databases. To summarize, the main findings of this research are as follows: (1) the majority of the studies concerns two roles, i.e., either capturing and structuring knowledge or separating domain knowledge and operational knowledge; (2) all ontologies apply deficient foundational ontologies, languages, and methodologies when developing ontologies for VRT; (3) there is a general lack of capturing perdurant knowledge in ontology design; and (4) there are key design elements that are considered crucial for designing an ontology for VRT. Further directions have been provided to contribute to the body of knowledge by recommending the right design elements that could produce idealistic and ubiquitous ontologies to facilitate VRT development throughout its life cycle. © *2022 SPIE and IS&T* [DOI: 10.1117/1.JEI.32.2.021403]

Keywords: Ontology applications; virtual reality; training and education; design components; training scenario; domain knowledge.

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1 Introduction

In recent years, as a result of advanced computer technology, the attention in VR has seen an excess in various domains. VR is defined as "an advanced form of human– computer interface that allows the user to interact with and become immersed in a computer–generated environment."[1] The immersive technology, in VR, is supported by sophisticated output devices, such as head mounted displays (HMDs). This technology makes the immersive environment closer to reality. It generates an experience for the user that is usually not possible in the physical real world. Using devices such as VR glasses, helmets, or HMDs allows users to smell, see, hear, and touch everything that exists in a VE. Moreover, the progress in VR technology from the past, present, and future has been outlined by Cipresso et al.[2] They described how VR for education and training has progressed and grown well, mainly as VR equipment and technology have become cheaper. Because of this, there has been a dramatic increase in the usage of this technology in various domains. The most frequent usage is in entertainment, such as gaming and movies. In robotics, with emerging advanced technology (e.g., HMD, haptics, gloves), VR has

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become connected to telepresence and telerobotic systems for controlling robots. In science and psychology, VR provides a significant and cost-effective tool through which users can interact and replicate in a safe and controlled environment. In airline systems, VR provides a platform to carry out flight simulations. In healthcare, surgery training is done through VR. Ophthalmology and laparoscopic procedures are some of the common fields using VR for surgery training.[3] Although it is hard to classify all VR types and systems, the major configurations fall into three main groups, with each group being classified based on the sense of immersion that it provides. These include full immersive applications (e.g., HMD and CAVE), semi-immersive VR (e.g., large screen monitor, large screen projector system, and multiple television projection systems), and nonimmersion (desktop) systems (e.g., standard high-resolution monitor).[4]

Although VR technology is not really new, the disciplines in VR application development (VR development, for short) are still in their infancy stage; one of the major reasons for the adoption level is entirely unclear and still under research.[5] Another concern relates to the fact that VR is relatively expensive, complex, and time consuming, and it requires a good amount of background knowledge to master it.[6–8] The lack of understanding of the domain's knowledge additionally creates a huge gap between domain experts and IT experts who wish to simulate. Other points reported by Marion et al.[9] were that the learning scenario models included into VR tools usually have two problems: (i) the models do not describe the activities involved in the virtual environment (VE) in a more comprehensive and systematic educational way and (ii) they are usually not reusable because they are only designed for a specific domain.

In general, virtual reality training (VRT) increasingly becomes difficult because it relies on a huge amount of knowledge that needs to be designed and captured. This is one reason for the development process being time consuming and complex.[10] For the sake of reducing the production time, the knowledge should be developed in a way that can allow reuse across several training domains. Therefore, explicit knowledge must be provided using well-known mechanisms.[11]

Introducing ontology as a conceptual tool to capture knowledge is the right decision; it was defined as "explicit specification of a conceptualization."[12] This is because there is empirical evidence of the benefits of utilizing it in various activities in VRT,[11,13–15] specifically the activities during VR life cycle development including VR requirements capture, storyboarding, design and construction, evaluation, and so on. Ontology could help to facilitate the implementation process during VR design, for example. It can bridge the communication gap between IT designers (on the one hand) and domain experts (on the other hand). In addition, the involvement of domain experts is a key feature of VR development success. One of the key roles of ontology is to facilitate communication, where both the domain experts and the stakeholders can better communicate with each other to reach an agreed specification model.[11,16,17] This approach helps with earlier detection of any design error.[18] However, the progress is slow, and the success stories of ontology applications in the VRT domain are not well reported.

Implementing ontology in VRT is not an easy task, and many adopters, from users to designers, have faced challenges in different situations. The absence of a high achievement rate in implementing ontology-driven VRT calls for deep comprehension of the process. To lower the failure rate of ontology applied to VRT, a study of the understanding of how ontology has been used to manage the learning scenario model, behavior, and interaction inside VR is required. Therefore, with a particular insistence on VRT, this paper presents the first attempt to establish a common understanding related to ontology for VRT. This paper subsequently strives to address the next main research questions:

RQ1: What are the ontology roles that are used to facilitate VRT development?
RQ2: What are the design components that are used in designing ontology for VRT development?

We start this paper by giving an overview of VR and ontology in Sec. 2. Next, in Sec. 3, we briefly explain a review method applied in this paper. Then, in Sec. 4, we present the related articles on ontology developed for VRT domain and further analyze them accordingly. In Sec. 5, the previous knowledge about selected papers is summarized. In the discussion, in Sec. 6, we mainly explain the findings of the review. Finally, we conclude this paper in Sec. 7 with recommendations.

2 Literature

VR has been applied for a variety of purposes. Its benefits and applications have been explored in several scenarios and projects. Nowadays, VR is mostly integrated into training, education, and teaching in several areas. Immersive technology is one key feature in VR technology, in which users can experience the feeling as part of a virtual world. They entirely lose the awareness that they are really in a computer-generated word. The emergence of the latest technology, such as HMDs, increases the level of immersion. As a result, VR has become more attractive than ever before.[19] However, the process to develop such a VR application for training and learning is complex and requires a long development life cycle, as a result of dealing with a very knowledge-intensive task. For example, capturing knowledge on the "know-how" among ophthalmologists (experts) conducting a cataract or glaucoma surgery, where any trivial mistake can potentially cause blindness. Bridging the knowledge between the ophthalmologist and VR experts is not a straightforward job. Another example is the knowledge in relation to cognitive skills to improve the way to solve a problem and make a decision, which is essential and has to be captured explicitly and represented in a well-defined ontological model as a basis for VR development.

A classic definition of ontology is "A formal, explicit specification of a shared conceptualization."[20] It was recently defined by extending the latter with new interested factors that really describe the major significance of ontology, whereas Feilmayr and Wöß[21] defined it as "A formal, explicit specification of a shared conceptualization that is characterized by high semantic expressiveness required for increased complexity." Semantic expressiveness is defined as the degree of explicit representation of domain interest. The complexity term refers to the involved number of concepts and their relationships in any ontology. The latter definition will be adapted throughout this research. An explicit specification of a conceptualization is an ontology, which is a conceptual model (knowledge-based model) and has been identified as a prominent tool to represent shared knowledge explicitly.[16,22] Unfortunately, existing VR development methodologies,[23,24] do not pay much attention to having knowledge-based models explicitly, throughout the VR methodologies or development life cycle.

Ontology is developed for many objectives of use, and it is represented at various levels of abstraction. According to Guarino,[25] ontology can be classified based on the level of abstraction into four categories including: top-level ontologies (upper ontology), domain ontology, task ontology, and application ontology. A variety of entities and engineering components of ontology are employed to design ontology depending on the problem that it is being addressed. These include endurants, perdurants, methodologies, tools, and languages.

Endurants and perdurants entities, for example, are connected to their behavior in time. Researchers say that "Endurants are entities that are in time; however, they lack temporal parts (so to speak, all of their parts flow with them in time). Perdurants, on the other hand, are entities that happen in time, and can have temporal parts (all their parts are fixed in time)."[26] Endurants include, for example, objects or substances, whereas perdurants include parts such as processes, states, or events.

Several methodologies, on the one hand, have been developed for designing ontologies either from scratch or by reusing existing ontologies. The process of building an ontology is similar to a craft rather than an engineering task. Each designing team or group can follow its own principles and decide the criteria and phase that are needed to be implemented and those that can be skipped. This of course would depend on the scale of the ontology that one intends to build.[27] The following are some types of methodologies: Uschold and King's method, NeOn methodology, Gruninger and Fox's method, and Methontology method.

On the one hand, the concerns about ontology tools have reached an unexpected level over the last decades. The objective of these types of environment is to offer support to the most actions involved in the ontology development life cycle. In addition, they offer significant features, such as importing, exporting, visualizing, and editing ontologies.[28] OntoUML lightweight editor (OLED),[29] Apollo, OntoStudio, Swoop, Protégé, and TopBraid are well known tools of ontology that have been indicated in many reports, such as Trokanas and Srai's work.[30]

On the other hand, according to Guizzardi,[31] the aim of languages is to explicitly represent real world phenomena and support human activities. These can include understanding (learning), communication among users, and problem solving. In literature, many languages exist for representing domain knowledge. They are sometimes given names as domain modeling languages such as LINGO, semantic data modeling languages such as entity relationship (ER), or ontology representation languages such as Web Ontology Language (OWL). In this study, these languages are referred to as conceptual modeling languages.[31]

3 Review Method

A comprehensive systematic review method of published papers up to the year 2020 was carried out. Noting this, this review was conducted based on systematic literature review (SLR) methodology,[32] which consists of many stages including revision planning, research identification, selection of primary studies, and classification.

3.1 *Revision Planning*

Revision planning is the first stage, when a review protocol is specified before starting the process of systematic review, which is significant of any SLR. The procedures for application of an SLR help specify a review protocol and its components. The protocol's components of this study consist of the revision objectives, selection criteria for including and excluding studies, and research questions.

The aim of this review is to explore how ontology has been applied in the development process for designing VRT in general areas. The subquestions which are answered by this study are listed as below:

- What are the ontology roles that are used to facilitate VRT development?
- What are the design components that are used in designing ontology for VRT development?

3.2 *Research Identification*

Research identification is also named screening for inclusion, and accordingly practical inclusion and exclusion criteria are provided. Reviewers here should explicitly justify the reasons for considering or eliminating studies. They also select the electronic databases and keywords.[32] In this review, a set of keywords were applied, including "ontology and virtual reality" or "ontology and teaching" or "ontology and training" or "ontology modeling simulation surgery." Subsequently, the electronic databases used include Springer, Science Direct, IEEE Xplore Digital Library, Google Scholar, ACM, Web of Science, Emerald, Taylor & Francis Online and Wiley Online, Cambridge Journal Online, and SAGE. In addition, inclusion and exclusion criteria were applied. Only published studies between January 2014 and July 2021 and related to ontology using VR for training, learning, and teaching were included. On the other hand, the studies were excluded if they were written in a language other than English; if they did not present the ontology long way with components; if the focus was on ontology for representing three-dimensional (3D) content related to appearance, geometry logic, and space; or they were a poster, sessions, slides, interviews, or news items.

3.3 *Selection of Primary Studies*

At this stage, the reviewers conducted the literature search. It enabled them to extract as many primary studies related to the research questions as possible. They should also describe and justify how they maintained the comprehensiveness of the research. To select the primary studies. two types of searches were applied, i.e., automatic and manual searches.

3.3.1 *Automatic search*

At this stage, a set of keywords were first applied in the electronic bases to retrieve the first collection of papers. Papers were retrieved based on title as the first step. During Step 2, duplicate studies were removed using either Mendeley software or manually. The latter bibliographic packages are extremely beneficial for arranging as many numbers of references as possible that can be collected from different sources. It automatically elicits information from any added PDF, comment, or highlighted text in papers and shares it with others.[33] In addition, it can help detect duplicate studies.

In Step 3, keywords and abstracts were reviewed, and papers were excluded when the inclusion criteria were not met. Abstracts with insufficient data were left to the next step. The complete texts for the selected studies were analyzed in step 4 using inclusion and exclusion criteria. With the purpose of increasing the comprehensiveness of research, the authors went through the list of references that were included in previous stage. This approach, called the snowballing process, tracks the references of references.[34] This kind of mechanism is used in addition to the common search that uses an electronic database. It is applied to identify additional related papers through the reference list and to make sure that no studies has been left out. Therefore, it helps build a comprehensive literature.

3.3.2 *Manual search*

At this stage, papers were retrieved (using step 1) from the listed references of previous research (automatic search). Meanwhile, steps 2 to 4 were again carried out. In step 2, the duplicate studies were removed. Then, abstract, keyword, exclusion, and inclusion criteria were applied in step 3. Finally, in step 4, a full text search was performed, and exclusion and inclusion processes were conducted (see Fig. 1). Overall, this method confirmed that there was no study left out, other than the 16 studies of this research, which were further analyzed in depth.

3.3.3 *Quality assessment*

This approach is considered to be an addition to common inclusion/exclusion criteria and is critical for examination of the quality of the extracted studies. It aims to weigh the significance of individual studies as the results are analyzed. Authors should clearly formulate the applied criteria to evaluate the quality of papers. At this stage, quality assessment (QA) was carried out on the papers that had been selected from the first and second iteration, forming a total of 26 papers. QA was achieved by the scoring technique to obtain relevant studies that can assist in addressing the research questions. Five QA questions were formulated to evaluate the relevance and quality of the selected papers. These are presented in Table 1.

Q1, Q2, Q4, and Q5 were adopted from the literature, whereas Q3 was created based on the scope of research. Each question has either two or three choices for the answers. Q1, Q2, and Q5 were given two options for the answers: yes or no. When the answers were yes or no, the papers received a score of 1 or 0, respectively. In addition to these, Q3 and Q4 allowed a third option (partly) by giving a 0.5 score to each study evaluated at low contribution. Consequently, the quality score for a particular study was achieved by computing the sum of all of its scores of the answers to the QA questions (see Table 2). This paper's authors, on the one hand, discussed all of the emerged discrepancies on the QA results to reach a consensus. On the other hand, the reliability of this result was established by accepting only the relevant studies with a quality score equal to or greater than 3. As a result, no paper was excluded from the primary studies. Finally, 16 relevant studies remained.

3.4 *Classification*

This stage concerns synthesis studies, which encompass gathering and summarizing the data extracted from the primary studies by applying suitable techniques and strategies such as quantitative and qualitative methods. Once the primary studies were reviewed in detail, they were categorized according to several criteria, including type of ontology (domain, application, and top level ontology) as defined by Guarino,[25] components of ontology engineering (methodology, tool, and language) as described by Corcho et al.,[28] domain area (industry, art, healthcare, etc.), ontology's roles, and finally endurants and perdurants as explained by Gangemi et al.[26]

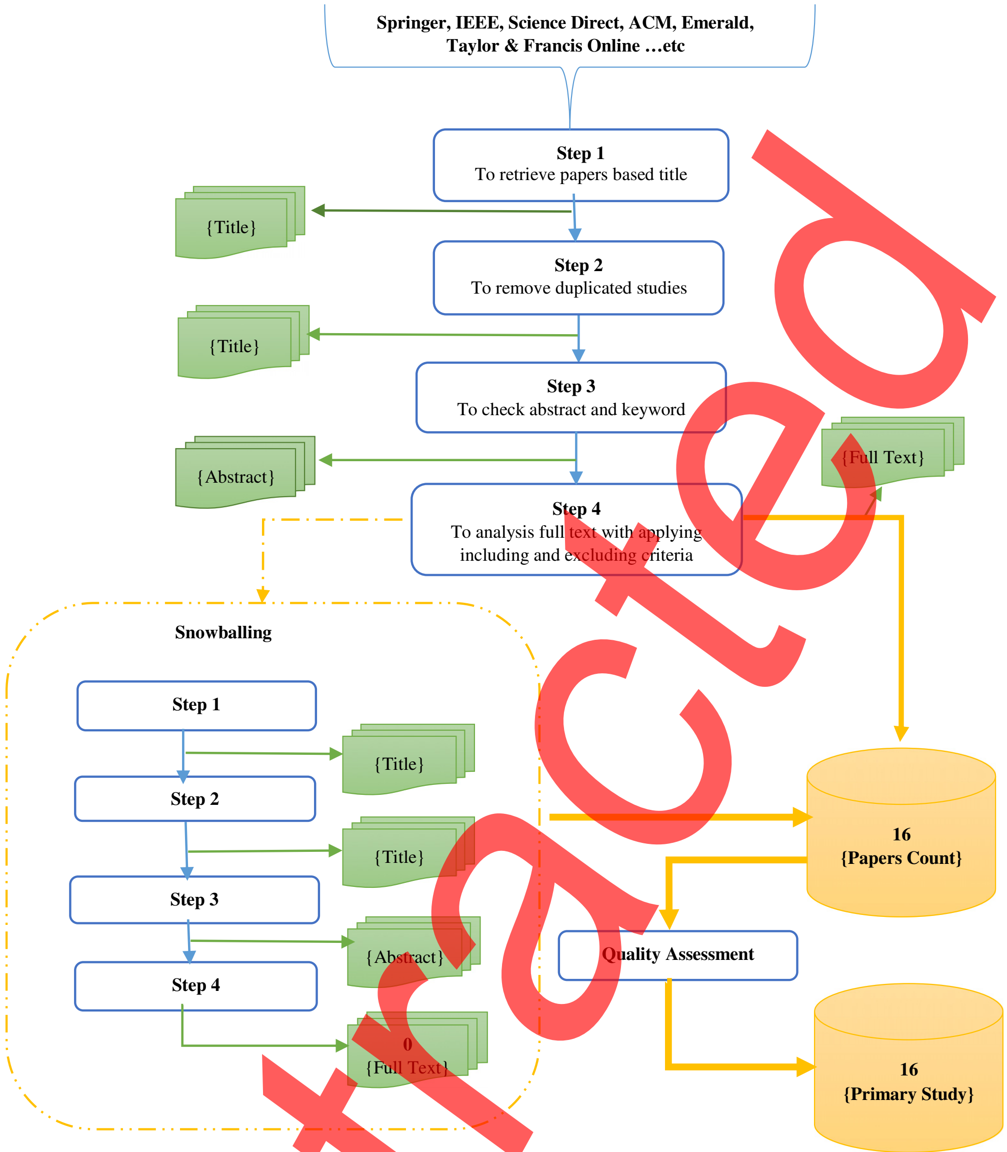

Fig. 1 Research design.

Table 1 Quality of assessment criteria.

N	Questions	Optional answers
1	Is the paper based on research (or is it a discussion paper based on expert opinion)?[35]	Yes = 1, no = 0
2	Is there a rationale for why the study was undertaken?[36]	Yes = 1, no = 0
3	Are the design components clearly presented?	Yes = 1, partly = 0.5, no = 0
4	Are the proposed concepts/relations clearly described?[37]	Yes = 1, partly = 0.5, no = 0
5	Was the ontology evaluated?[16]	Yes = 1, no = 0

4 Results

In this section, the ontologies were classified into categories, such as industry, serious game, military, art, healthcare, and business sector. A brief description of each ontology is presented

Table 2 The included studies in QA approach.

ID	QA1	QA2	QA3	QA4	QA5	Score
S1	1	1	1	0.5	1	4.5
S2	1	1	1	0.5	1	4.5
S3	1	1	1	1	1	5
S4	1	1	1	1	1	5
S5	1	1	0.5	1	1	4.5
S6	1	1	1	1	1	5
S7	1	1	0.5	1	1	4.5
S8	1	1	1	1	1	5
S9	1	1	0.5	1	0	3.5
S10	1	1	0.5	1	1	4.5
S11	1	1	1	1	1	5
S12	1	1	0.5	0.5	1	4
S13	1	1	1	1	1	5
S14	1	1	1	1	1	5
S15	1	1	1	0.5	0	3.5
S16	1	1	0.5	1	0	3.5

in the following section along with identification of the most important components in ontology engineering including the methodology for developing ontology, tool, and language.

4.1 *Industry Sector*

The ontologies in this field were developed to care about industry and construction domains. They assist with capturing enterprise data, enhancing interoperability, and sharing knowledge between two systems, e.g., building information modeling (BIM) and VR (see Table 3). The following sections provide a summary for each ontology.

4.1.1 *VISTRA ontology*

Although the idea of VRT is not really new, it does not find its way into everyday practice within industry. The key reasons behind this are a lack of effort on creating a training scenario in an explicit manner and missing methodology that helps integrate or reuse the existing data structure. Ontology therefore was selected as a semantic modeling tool due to its benefits in terms of expressiveness, verification, integration, and reusability. Gorecky et al.[38] used the VISTRA training system project. The previous technology aimed to train employees performing their daily activities on a standard assembly sequence. This system provides a robust example of how the application of ontology enables facilitation of the reusability of enterprise data for several computer applications (e.g., knowledge management and training). It is further proof of how the semantic technology's usage supports the integration of heterogeneous data, guarantees the data consistency, and allows for a reasoning process. In addition, this helps reduce time and effort for building new virtual training scenarios. The architecture of the VISTRA system consists of three essential components. The central and first one is the VISTRA Knowledge Platform. Its role is to receive enterprise data in different formats; these data include users, products, teams, processes, and so on. The second one is the VISTRA Training Simulator in which virtual training is

Table 3 Industry sector.

Reference	Ontology name	Purpose of ontology	Design component					Evaluation
			Type of ontology	Design approach	Language	Tool	Methodology	
Gorecky et al.[38]	VISTRA ontology	• To share interoperability and unambiguous data with IT designer • To explicitly capture and structure training scenario training • To enhance reusability • To facilitate query and reasoning abilities • To reduce time and effort for building VRT scenarios	Domain ontology	Endurant Perdurant	Semantic triple store OWLIM, OWL	Protégé	NM	Yes
Dris et al.[39]	IVE ontology	• To enhance the use of BIM • To provide interoperability between BIM and VE • To explicitly author scenario training	Domain ontology	Reused IFC ontologies Endurant Perdurant	OWL	Protégé	Noy and McGuinness	Yes
Vincent et al.[40]	Inoovas ontology	• To provide authoring tool for AVR operations • To enhance interoperability • To provide guidance how to do tasks	Domain ontology	Endurant Perdurant ontology	UML	NM	NeOn methodology	Yes
Filho et al.[41]	Ontology for operator training simulator scenarios	• To facilitate the development process of training scenario • To enhance common language sharing among training scenarios and stakeholders • To explicitly capture and structure training scenarios	Domain ontology	Endurant Perdurant	OWL-DL	Protégé	MCCA	Yes
Walczak et al.[42]	Ontology for VRSEd project	• To facilitate the development process of training scenarios	Domain ontology	Endurant Perdurant	RDF, RDFS and OWL	NM	NM	Yes

NM, not mentioned.

conducted. The last one is the VISTRA Knowledge Sharing Centre. It is responsible for organizing training sessions and evaluating training results.

At the first step, two types of ontologies were used. Domain ontology conceptualized the knowledge related to manufacturing, whereas task ontology conceptualized the training activities. At the second step, both of these ontologies were merged into an application ontology for VRT as a way to specialize the task and domain. Thereby, four ontologies were designed to specify the structure data used in the VISTRA system including the assembly process model (DO), plant model (DO), user model (TO), and statistics model (TO). Graphical ontology editors such as Protégé were used as tools to develop this ontology. All OWL ontologies were designed using the Protégé tool and subsequently loaded into the semantic triple store (OWLIM). The ontology was evaluated within the system by more than 50 users. As a result, a prototype was developed and the VISTRA system was implemented. It is worth noting that the methodology for developing ontology was not mentioned in this work.

4.1.2 *Interactive virtual environment ontology*

Dris and his colleagues[39] proposed an ontology that can help improve the use of BIM models as a virtual interactive environment generator. At the same time, it enabled interoperability between BIM and VE. It was a risk hunting application as VRT was supported by BIM to reduce the risk faced by workers within construction areas. BIM is considered an approach that helps minimize the time spent in designing VE as a model for providing realistic 3D VE in the construction sector.

To design this ontology, the authors reused industry foundation classes (IFC) ontologies[43] as the first step. They also designed the model for virtual risk hunting to randomly self-produce sever errors, which is based on IFC ontology. These errors were divided into two groups. One is error insertion, which defines different types of errors to be automatically applied in VE. The role of IFC ontology is to discover any possible incident of each fault that can be performed by modifying, adding, or removing objects inside the VE. The second one is error scriptwriting. It was written by the authors to describe the scenario of the required behavior for each error. This was defined with the help of the #SEVEN model.[44] It is based on a petri net model and the association of sensors that addresses the interaction side with VE. Petri net is another well-known language used to model dynamic aspects of the domain. Noy and McGuinness's methodology, Protégé software, and OWL are ontology engineering components used to build this ontology.

Three sheets of questionnaires were designed to evaluate the ontology's effectiveness. The first was conducted prior to training to classify the trainee in terms of knowledge and technology. The second was done after training to evaluate knowledge acquisition. Finally, a month later, the same questionnaire was provided to them again.

4.1.3 *Inoovas ontology*

Inoovas ontology was designed by Vincent et al.[40] Its aim is to solve the problem of how all resources including people (mechanical or electrical designer, IT maintenance), heterogeneous software, and tools (VR, AR) can work together; they were remotely joined in the procedure with an effective data exchange method in an augmented and virtual reality (AVR) environment. Therefore, Inoovas ontology provides several advantages. It first describes and designs a guiding procedure on how to use it in VR for training purposes. In the same way, it may help guide the operator to perform tasks in AR. Second, it assists in reducing time to author task operations inside an AVR environment. Finally, allowing the interoperability among various applications and tools can be an additional benefit.

Inoovas ontology represents the knowledge base of the company that contains three important parts. Figure 2 presents the real thing that describes the physical parts of the system, data exchange with the system, and other classes of managing requirement on the system. The twin thing represents the 3D model of the system. Finally, real and twin thing ontologies concern defining AR classes. Vincent et al.[40] used UML to represent the classes involved in ontology. This paper used the NeOn methodology, but the editor tool was missed in this paper. Inoovas was

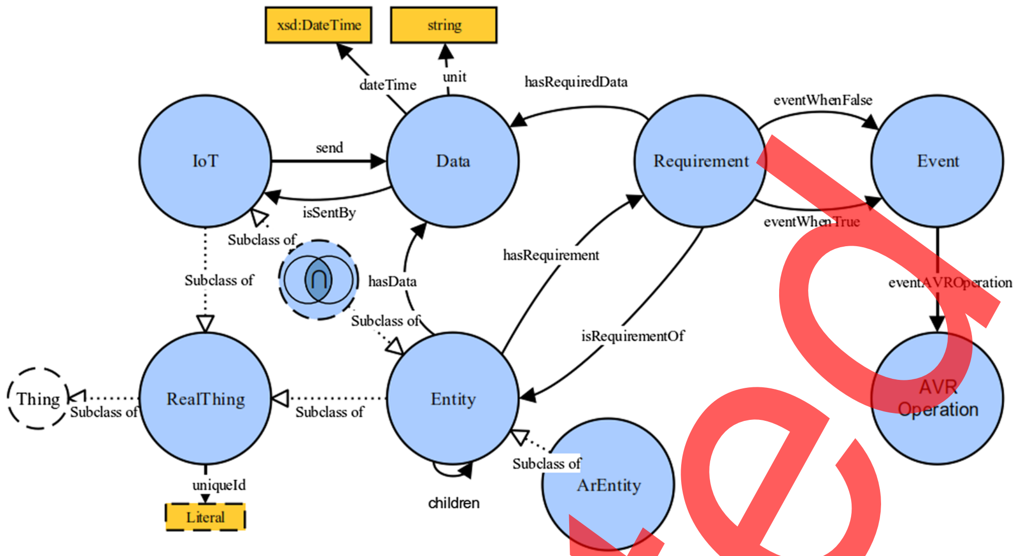

Fig. 2 Inoovas ontology by Vincent et al.[40]

evaluated by developing an application named MProd. This application is grounded on the Inoovas ontology concepts and properties.

4.1.4 *Ontology for operator training simulator scenarios project*

This ontology is about designing error and training scenarios for electrical power system operators. This scenario was developed according to accident reports (consisting of human error scenarios).

Construction of simulator training scenarios has posed various challenges. Dealing with a multidisciplinary team of experts could cause several obstacles including producing implicit training scenarios and sharing a lack of knowledge among team members. Filho et al.[41] attempted to build an ontology that facilitates the development process of training scenarios and enhances common language sharing among stakeholders. The OWL-DL language was used to design ontologies, with the help of the Protégé tool. The incident scenario conceptual model was the applied method to develop the ontology of this study. The designed ontology consisted of two ontologies: training and error scenario ontology. Both are subclasses of the scenario ontology. In addition, endurant and perdurant entities were applied to represent things and events that are needed to be in the training scenarios. A case study was the validation pathway to evaluate this ontology-based correctness and completeness of the terms.

4.1.5 *Ontology for VRSEd project*

Walczak et al.[42] proposed a new method in designing a VR training scenario for electrical operators with the help of semantic web technology. The semantic web latter technology enables knowledge representation. Both the semantic modeling approach and the user-friendly VRSEd application were implemented as an expansion of Microsoft Excel. Domain experts were enabled to build training scenarios utilizing domain concepts defined by ontologies. RDF, RDFS, and OWL standards were used to implement the scenario ontology.

RDF is a semantic language to describe the information coming from the web.[28] Therefore, all ontologies that were written by RDF can be understood and implemented by any computer system.[45] Moreover, the format of Extensible Markup Language (XML) was used by RDF to represent ontology. As such, this feature makes ontology more interoperable among a variety of system agents. Now, RDF is widely utilized as a representation formalism tool due to the fact that it can significantly help represent ontology in defining the information that needs to be exchanged among different agents or software.[46] The RDF schema was also developed by W3C, which they extended to produce RDFS.[45]

Table 4 Military sector.

Reference	Ontology name	Purpose of ontology	Design component					Evaluation
			Type of ontology	Design approach	Language	Tool	Methodology	
Elenius et al.[47]	SAVE	• To explicitly capture and structure training scenarios • To evaluate student action and provide feedback • To facilitate reasoning about student action • To provide guidance to student during training	Domain ontology	Endurant Perdurant	Flora2	Sun-flower	NM	Yes

NM, not mentioned.

However, the tool and methodology are not mentioned in this paper. The new method was implemented and demonstrated as a desktop application for developing VR scenarios, which was further evaluated by domain experts.

4.2 *Military Sector*

This category focuses on the military field. Therefore, Table 4 briefly illustrates ontologies that are used to train military students in certain tasks in VE such as disassembling and assembling a rifle. Two ontologies are presented as follows.

4.2.1 *SAVE ontology*

Elenius et al.[47] designed a framework called semantically enabled automated assessment in virtual environments (SAVE). This ontology provides many benefits. For example, it can evaluate student performance and offer significant feedback to enhance their learning skills. The problem in the traditional method of training is that direct observation by the trainer is required for some functions such as assessment and context awareness feedback. This ontology tries to provide an automated approach using the semantic method. This helps describe or facilitate the action, event, and rules including disassembling and assembling of a rifle. SAVE ontology reused Sunflower, which is an integrated development environment for ontologies and rules. Sunflower has a set of libraries and tools based on the Flora 2 language, which is a fully expressive language. Its root is based on OWL in descriptive language. SAVE uses four components, namely an ontology of components (physical objects) (see Fig. 3), rules for creating components (and their subcomponents), an ontology of actions, and rules for performing actions on components. However, the adoption methodology in this project again is not declared. In the evaluation part, all ontology models were tested by subject matter experts.

4.3 *Art Sector*

Table 5 presents all ontologies related to the art field. They facilitate the interaction between human and VE to help learners understand and learn art by just using their computers.

4.3.1 *Ontology for choreographies of virtual actors*

VR is more heterogeneous with regard to the included data model and programming language in the development process. Its design is time consuming and difficult. Therefore, Silva et al.[10]

```
LowerHalf :: PhysicalObject [|
  selector {1..1} => Selector,
  magazine {0..1} => Magazine,
  magazineReleaseButton {1..1} => MagazineReleaseButton,
  hammer {1..1} => Hammer,
  trigger {1..1} => Trigger,
  pivotPin {1..1} => PivotPin,
  takedownPin {1..1} => TakedownPin,
  boltCatch {1..1} => BoltCatch,
  buttStock {1..1} => ButtStock,
  lowerReceiverExtension {1..1} => LowerReceiverExtension,
  bufferRetainer {1..1} => BufferRetainer
|].
```

Fig. 3 Ontology using flora language by Elenius et al.[47]

attempted to capture and represent knowledge related to choreographies to visualize it inside virtual world. Choreographies of virtual actors are explicit contents that help describe the collection of tasks that can be done by users and 3D actors. The ontologies were presented using the description logics (DL) syntax. Ontology development methodology and tools were not indicated in this paper. The foundational ontology type was also missed. In this study, ontology was classified into choreography's domain (independent and dependent) and VE platform (independent and dependent).

These ontologies were mapped to generate automatic development of particular choreography domain from top level independent ontology. This helps reduce time and effort for developing choreography that needs to be staged in other virtual platforms. This ontology also uses a reasoning process to evaluate the semantic perfection of the knowledge base, when any insertion or elimination of fact occurred. For evaluation purposes, the OpenSimulator and messaging platform were used to evaluate the practice of this ontology by Silva et al.[10]

4.3.2 *Ontology for virtual shadow play performance*

In the VR domain, designing interactive animation is still a challenge and is labor-intensive because, during the development process, many functional requirements including massive data assets management, graphics, physics, etc. should be handled. The purpose of Liang and his team's work[15] was to design a semantic framework to develop collaborative animation for classical shadow play art (shadow puppetry). In the same way, it enabled prompting reusability of animation properties. As a result, the development process was facilitated and extended. Two specific ontologies were built. The first one was hand- and gesture-based interaction ontology (HGBIO) (see Fig. 4). It included three subclasses, i.e., human, device, and method. Each subclass consisted of several subclasses. The role of HGBIO was to capture and represent the things that exist in the shadow puppetry domain, whereas digital Chinese shadow puppetry assets ontology, as a second ontology, also contained various subclasses such as role, prop, scene, and music. Each of these subclasses had superclass.

For instance, in Chinese shadow puppetry, human characters play four roles including Jing (painted face, male role), Dan (female role), Sheng (male role), and Chou (joker male role). Having OWL enables integration of semantic web rule language (SWRL) rules, which can be represented by utilizing SPARQL queries. The feasibility verification of ontology was performed using user experiences test of the ontology. At first, more descriptions of the operation of the system and 15 min of training were delivered to seven users. Then, they were separated into two groups to conduct a qualitative test. The first three users tested ontology-based assets retrieval, while the second four users, who were young children, examined the interaction comfort. As a result, both groups provided positive feedback regarding the retrieval of material from animation resources, freedom of movement, ease of use, and naturalness.

Table 5 Art sector.

Reference	Ontology name	Purpose of ontology	Design component					Evaluation
			Type of ontology	Design approach	Language	Tool	Methodology	
Silva et al.[10]	Ontology for choreographies of virtual actors	• To author domain VR knowledge-related choreographies • To reduce time effort of development • To provide reasoning for evaluating semantic integrity	Domain ontology	Upper ontology Endurant Perdurant	DL	NM	NM	Yes
Liang et al.[15]	Ontology for virtual shadow play performance	• To author domain VR knowledge for learning process • To enhance reusability of the animation product • To facilitate the development process • To support data retrieval through reasoning	Domain ontology	Endurant Perdurant	OWL, SWRL	Protégé	NM	Yes
Yeh and Huang[48]	BKOnto	• To capture, represent, and support VR knowledge base • To provide storyline of information	Domain ontology	Endurant	OWL	NM	NM	No

NM, not mentioned.

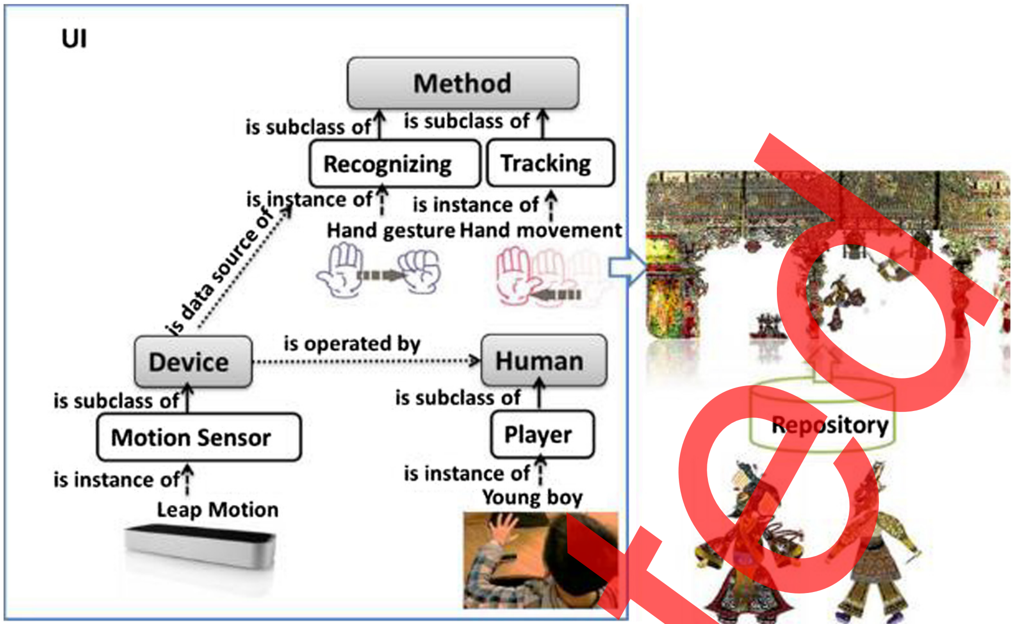

Fig. 4 HGBIO by Liang et al.[15]

4.3.3 *BKOnto ontology*

Yeh and Huang[48] developed a virtual exhibition system based on ontology knowledge. This ontology was designed based on biographical history, which is called BKOnto. The ontology's aim is to provide basic knowledge to assist virtual presentation. This can appear by processing biographical history (e.g., biographical events, person, place, and image) on the semantic web with the help of VR technology. This ontology behaves as a storyline while assisting in providing structure definitions that systematically present the historical materials and events.

BKOnto used the OWL mark-up language to describe cognitive knowledge bias for biographical historical material. This was further transformed into VR exhibition space, which enabled users to easily navigate the semantic structure in the form of a 3D space. This form can be reused in museums as virtual exhibitions that facilitate managing historical material with a semantic structure through the internet and providing visual experiences of a temporal event for internet users. The tool, methodology, and validated design of BKOnto were not indicated in this study.

4.4 *Serious Game Sector*

The concern of this section is related to ontologies that were developed to ease the creation of scenarios of a serious game that fills the needs of trainees in VE. Table 6 shows some of them.

4.4.1 *PRESTO ontology*

The Plausible Representation of Emergency Scenarios for Training Operations (PRESTO) ontology was designed by Dragoni et al.[49] for the PRESTO project. This project tried to describe the behavior of an artificial agent in VE. The authors attempted to address the problems discovered, such as code programming of nonplaying characters' behaviors, which is usually not reusable and hard to modify. In addition, the development process is entirely time and effort consuming. Thus, the purpose of this ontology is to facilitate the development of a VR scenario and character behavioral model. It enhances the source code's reusability, and the VR developers are plugged to a variety of source coding and underlying 3D-libraries.

The OWL language and lightweight ontologies were used to enhance semantics and provide an explicit description of exciting scenarios in a VR environment. Descriptive ontology for

Table 6 Serious game sector.

Reference	Ontology name	Purpose of ontology	Design component					Evaluation
			Type of ontology	Design approach	Language	Tool	Methodology	
Dragoni et al.[49]	Presto ontology	• To author VR scenario • To allow the source code's reusability • To reduce effort and cost • To provide mutual understanding of domain interest	Upper level ontology	DOLCE Lightweight ontologies Endurant and Perdurant	OWL	NM	NM	Yes
Peeters et al.[11]	SBT Ontology	• To adhere reasoning process • To provide feedback-based error • To evaluate student competency • To create coherent storyline of training (scenario generator) • To reduce development time • To enhance reusability across training domain • To share common understanding among stakeholders	Upper ontology	Endurant Perdurant Reuse task analysis ontology	Frame-based ontology	Protégé Frames 3.5	Noy and McGuinness	Yes

NM, not mentioned.

Retracted

linguistic and cognitive engineering (DOLCE), as top level ontology, was applied to select the entities of a VR scenario. Endurants and Perdurants, such as example of entities, were used to represent physical objects and events existing in VR, respectively. However, tools and methodology were not clarified in this study.

The PRESTO ontology is composed of three parts: a top level part represented by DOLCE, a middle one that concerns all exciting entities in a VR scenario, and a last part describes the entities, objects, and behaviors occurring in a VR environment. For validation, modelers and developers were interviewed to evaluate the effectiveness and usefulness of the designed ontology-based system.

4.4.2 *Ontology for SBT*

SBT is an automated scenario-based training (SBT) intelligent system. A scenario generator in SBT is a critical component developed with help from ontology. Peeters et al.[11] developed an ontology for modelling the most important component in SBT, which was the training scenario. The lack of representation of the information in a consistent, generic, and unambiguous way was the problem that the used ontology tried to address. Therefore, the ontology helped to structure knowledge that is needed to perform an automated SBT. More clearly, it attempted to create a fitted learning scenario that fills the needs of trainees. Thus, the verity of benefits was included. For instance, the reasoning process was adhered to in this ontology and included various actions such as providing feedback when a student committed an error, evaluating student performance, deducing learner competency, and so on. It enabled reusability of ontology across various applications, training domains, and system designs. Sharing common understanding among stakeholders is also guaranteed, with the project team from domain experts to designers utilizing the representation in architecture and programming code description.

The ontology for SBT was built based on the method presented by Noy and McGuinness[50] and reused "task analysis" ontology by Van Welie et al.[51] to present links between event, procedure, role, and action. The upper ontology for SBT was organized into three sections: 1-training environment, 2-task domain, and 3-didactics. Frame-based ontology was reused and derived from semantic networks. This tool was specially selected due to its power regarding presenting knowledge involved in training. Moreover, it offers an explicit, semantic, and complete description of the propositional knowledge.[52] The format of frame was utilized to develop relevant knowledge for SBT. The validation and usefulness for upper ontology was tested by domain experts. They were asked to estimate the collective ontologies based on several criteria including clarity, coherence, representativeness, accuracy, completeness, consistency, and conciseness.[53,54] The prototype of the scenario-based training generator was further produced, and its outcome was tested in an experiment.

4.5 *Healthcare Sector*

Table 7 shows examples of ontologies designed to help the teaching of medical structures, generate significant content information, and provide various interactions. Several ontologies are explained as follows.

4.5.1 *Ontology for Smart Home Simulator project*

Baldassini and his colleagues[14] presented ontology for the Smart Home Simulator project (SHS). The main challenge was the ability to provide elder people a system that can enable them to follow an active and healthy lifestyle. Thus, the customization of the services was achieved by exploitation ontologies. Ontology endurants helped to model such things.

They include, for example, the health situation of users, surrounding domestic environments, and all comfort metrics and devices utilized by users. Basically, ontology was used to manage all heterogeneous data regarding users, surrounding devices, and environments. The reasoning tools in this conceptual model enabled a query process that provided the desired data to ensure that users followed the proper activities. The designed ontology relied on three ontologies that are based on several languages. These languages were the resource description framework—RDF

Table 7 Healthcare sector.

Reference	Ontology name	Purpose of ontology	Design component: Type of ontology	Design component: Design approach	Design component: Language	Design component: Tool	Design component: Methodology	Evaluation
Baldassini et al.[14]	Ontology for SHS project	• To customize the appropriate service to elderly people • To author domain knowledge for VR scenario • To retrieve desired data using reasoning tools	Domain ontology	Endurant	RDF, OWL	NM	NM	Yes
Ramírez-Fernández et al.[55]	VEULMoR ontology	• To explicitly author domain knowledge for VR training process • To facilitate the design of VE • To share common understanding	Domain ontology	Endurant Perdurant	OWL, UML	Protégé	Methontology	Yes
Tielman et al.[56]	Ontology for virtual coach	• To capture and represent knowledge and meaning of the real domain	Domain ontology	Endurant	Class diagram	NM	NM	Yes
Heyse et al.[57]	Ontology for VRET	• To capture and model the necessary domain knowledge • To deduce high-level knowledge using reasoning tools	Upper and domain ontology	Endurant Perdurant	Use case diagram, DL	NM	Co-design method	NM
Antoniou et al.[58]	ENTICE ontology	• To enhance the content development and facilitate the XR development process	Domain ontology	Endurant	RDF	NM	NM	NM

NM, not mentioned.

and OWL. The first ontology was used to describe the users' health situation, whereas the second one was utilized for description of the house and its structures, such as windows and doors. The last one was employed for the devices' representations. The ontology components, just like the tool and methodology, were not clarified. Task-based evaluation was applied to check the usability and ergonomics of the system. A number of healthy subjects (from 25 to 30 years old) were used. The aim of this kind of evaluation was to test whether the intended tasks were achieved or not.

4.5.2 *VEULMoR ontology*

Designing VR applications for upper limb motor rehabilitation is a difficult task. Designers are required to master various aspects including stroke-survivor, characteristic motor rehabilitation, interaction devices, and so on. Even though there are several recommendations in the literature on how to design VE, these are semantically heterogeneous; hence it is quite challenging to connect them with each other.

Understanding the key domain concepts in motor rehabilitation is one of the solutions. Therefore, Ramírez-Fernández et al.[55] designed the VEULMoR ontology. The proposed ontology helped capture domain expert knowledge and presented it in the ontology. This approach shortened the time and facilitated the development of VR applications. The VEULMoR ontology was designed with help of the Protégé editor, Methontology methodology, and the use of OWL language. Figure 5 shows the ontology representation using UML. The evaluation was implemented with therapists and patients in terms of patient safety and the administration of therapy.

4.5.3 *Ontology for virtual coach*

In Tielman et al.'s work,[56] an ontology-based question system was built to support a virtual coach. The latter technology was used to provide self-therapy for post-traumatic stress disorder

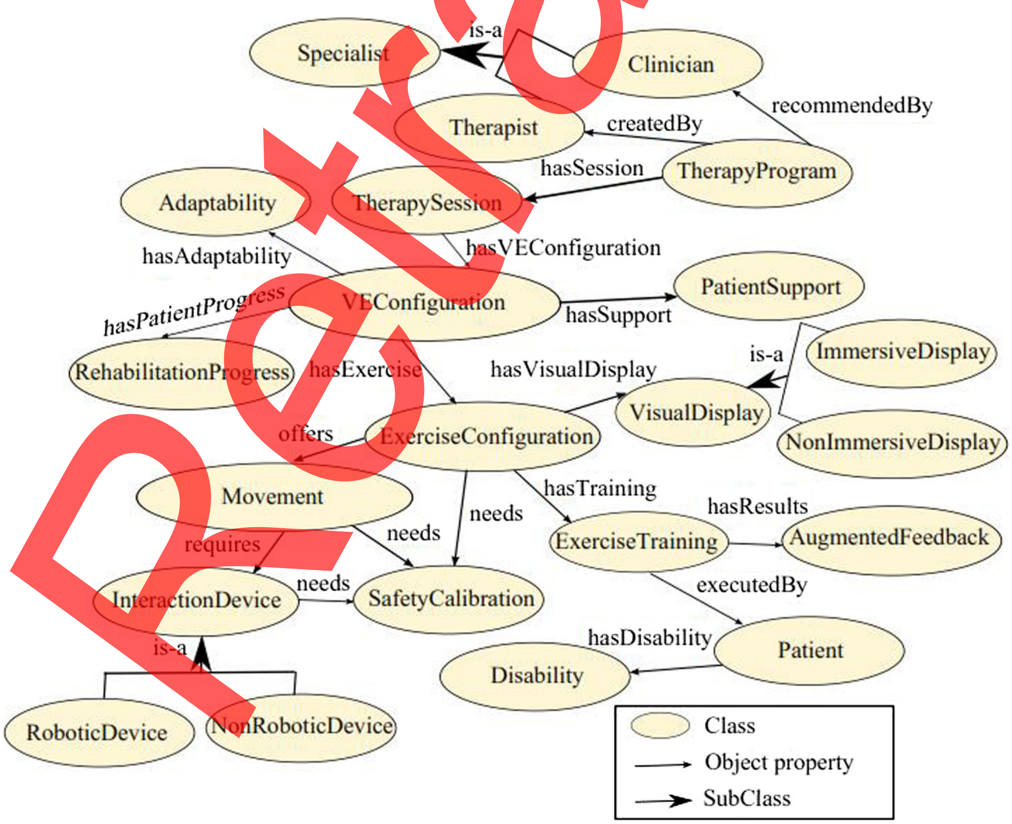

Fig. 5 Representation of VEULMoR ontology using OWL by Ramírez-Fernández et al.[55]

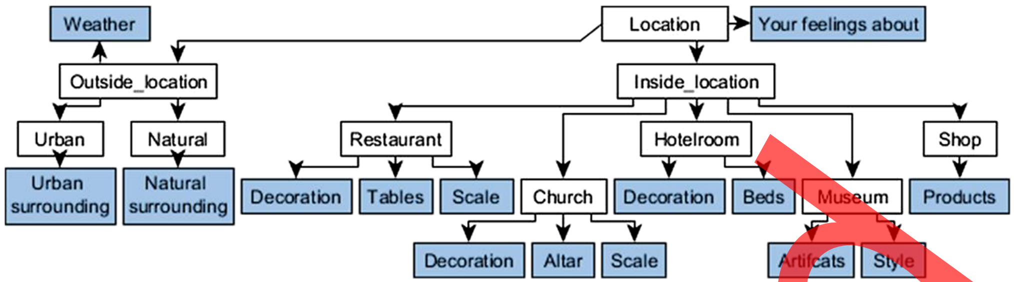

Fig. 6 Ontology of holiday moment locations by Tielman et al.[56]

patients, which enables patients to follow therapy at their own home. The vital side of this therapy is how to assist patients in recollecting their traumatic memories. Ontology, therefore, was applied to support a dialogue system in a virtual coach, in which it was utilized to capture and represent knowledge and meaning of the real domain (see Fig. 6). In this paper, the ontology was presented using a class diagram; however, the methodology and tool are not mentioned. The ontology-based system was evaluated using a within-subject experiment to confirm the performance of the ontology in helping patients to recollect their lost memories.

4.5.4 *Ontology for VR exposure therapy*

In this project,[57] semantic ontology was designed with the purpose of modeling the necessary knowledge (e.g., concepts and relation) in a way to represent the domain of anxiety therapy in VE. The aim of the designed ontology was also to provide semantic reasoning to deduce essential knowledge from low-level data in VR exposure therapy (VRET). This can be archived using a DL language, which permits the formulation of such rules. The use case diagram was utilized to represent the proposed ontology, which contains three layers of ontologies including foundation, domain, and application ontologies. The codesign method was applied to design the project's ontology, but the tool was missed in this study. The integration of the ontology inside VE and its evaluation was left to future work.

4.5.5 *ENTICE ontology*

The aim of immersive educational technology including augmented, virtual, and mixed reality (VR/AR/MR communally XR) is to facilities skills acquisition and knowledge retention in the healthcare field. Designing XR immersive educational content is considered to be the core challenge in terms of cost, effort, time, and resources required for developing. Therefore, Antoniou et al.[58] proposed an approach including the ENTICE ontology to enhance the content development and to facilitate the XR development process, such as digital asset discoverability and reusability through visual authoring tools. The medical ontology terms were represented using RDF. The integration of ontology into the XR environment and evaluation were planned as further research. The tool and methodology were not indicated in this project.

5 Summary

In Table 8, the ontologies are classified into categories along with identification of the significant roles of each ontology. In addition, Figs. 7 and 8 show the most used roles and trends, respectively. Finally, the most important components of ontology engineering are shown in Fig. 9–11.

5.1 *Ontology Role*

Different purposes have been revealed for designing ontology for VRT projects. On the one hand, as presented in the bar chart (Fig. 7), all designed ontologies took the benefit of both roles: (1) capturing and structuring training scenario and learning contents and (2) separating

Table 8 Domain area and roles of ontology for each study.

ID	Authors	Domain area	Roles of ontology
S1	Gorecky et al.[38]	Industry	CSTSLC, SDKFOK, RTC, EI, ER, FRP
S2	Dris et al.[39]		CSTSLC, SDKFOK, EI, ER
S3	Vincent et al.[40]		CSTSLC, SDKFOK, PGVE, EI
S4	Filho et al.[41]		CSTSLC, SDKFOK, RTC, ECASA
S5	Walczak et al.[42]		CSTSLC
S6	Elenius et al.[47]	Military	CSTSLC, SDKFOK, PGVE, FRP
S7	Silva et al.[10]	Art	CSTSLC, SDKFOK, RTC, FRP
S8	Liang et al.[15]		CSTSLC, SDKFOK, RTC, FRP
S9	Yeh and Huang[48]		CSTSLC, SDKFOK
S10	Dragoni et al.[49]	Serious game	CSTSLC, SDKFOK, RTC, ECASA, ER
S11	Peeters et al.[11]		CSTSLC; SDKFOK; RTC; ECASA; ER; FRP
S12	Baldassini et al.[14]	Healthcare	CSTSLC, SDKFOK, FRP
S13	Ramírez-Fernández et al.[55]		CSTSLC, SDKFOK, ECASA
S14	Tielman et al.[56]		CSTSLC, SDKFOK
S15	Heyse et al.[57]		CSTSLC, SDKFOK
S16	Antoniou et al.[58]		CSTSLC, SDKFOK

CSTSLC, capturing and structuring training scenario and learning content; RTC, reducing time and cost; EI, enhancing interoperability; FRP, facilitating reasoning process; ECASA, enhancing communication among stakeholders or applications; ER, enhancing reusability; SDKFOK, separating domain knowledge from operational knowledge; PGVE, providing guidance in VE.

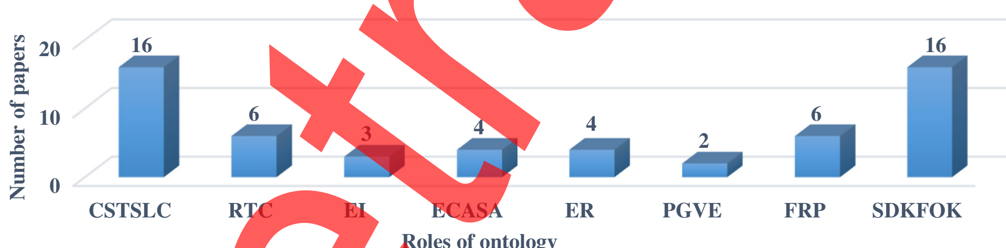

Fig. 7 The frequent used ontological role. CSTSLC, capturing and structuring training scenario and learning content; RTC, reducing time and cost; EI, enhancing interoperability; PGVE, providing guidance in VE; ECASA, enhancing communication among stakeholders or applications; ER, enhancing reusability; SDKFOK, separating domain knowledge from operational knowledge; FRP, facilitating reasoning process.

domain knowledge from operational knowledge as dominant roles. On the other hand, less than half ($N = 6$) used the facilitating reasoning process or reducing time and cost as a second reason for applying ontology in VRT. Less than a third, approximately equal numbers of ontological engineers, utilized ontology for enhancing reusability and enhancing communication among stakeholders or applications ($N = 4$).

Finally, a small number of studies utilized enhancing interoperability and providing guidance in VE with ($N = 3$) and ($N = 2$), respectively. As we can see from this (Fig. 7), several significant roles were scarcely applied in designing ontology for VRT in several areas. Due to this, more than half of the ontologies are lightweight ontologies in which the level of complexity is very low.

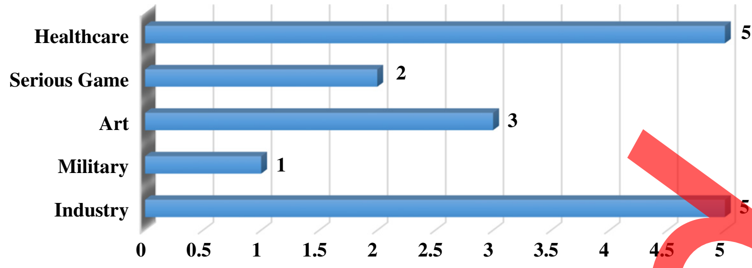

Fig. 8 Areas of designed ontologies.

5.2 *Ontology Domain*

The bar chart in Fig. 8 shows the state of the art of the interest domain of the ontological designers, which helps conclude the actual trend of designed ontologies for particular domains. Thus, several areas were revealed. For example, healthcare and industry were the highest interest areas with five studies each, followed by art and serious game with 3 and 2 studies, respectively. Other industries such as military were less represented with only 1 study.

Figure 8 clearly shows the trend of the current ontologies that are designed for VRT projects in healthcare and industry. Focusing in healthcare, for example, may be deduced by the success stories of biomedical data integration, in which ontology plays an essential role. These include gene ontology, the cancer biomedical informatics grid (caBIG), and so on.[59] Although all developed ontologies in healthcare attempt to represent training scenarios regarding certain areas, e.g., teaching human anatomy, providing therapy, or selecting the right diagnosis, none of them covered surgical procedures, which are more significant because of the requirement to enhance the cognitive skills of trainees.

5.3 *Ontology Languages*

Guizzardi[31] reported that any truth with regard to reality and semantic interoperability for a designed system highly depends on the existing utilized conceptual modeling that decides the level of explicitness and acuity for representing the interest domain. Nowadays, several languages exist; these include OWL, OntoUML, UML, RDF, LINGO, and ER.

This review revealed that the OWL language with a strong impact in semantic web gets a high rating. Eight studies chose this language in the design of their ontologies (see Fig. 9). UML, as a popular modeling language in software engineering, was the second choice with four designers, followed by RDF with three studies. However, languages such as frame-based, DL, and flora demonstrate a very low adoption among designers.

5.4 *Methodologies*

In software engineering, applying the wrong choice of methodologies can definitely lead to a poor design and software that is difficult to maintain. Similar to ontology, misuse or missing an ontological engineering methodology results in complicated ontology that limits its ubiquity. It has been reported that the existing methodology is still immature.[28,60,61] As shown in Fig. 10,

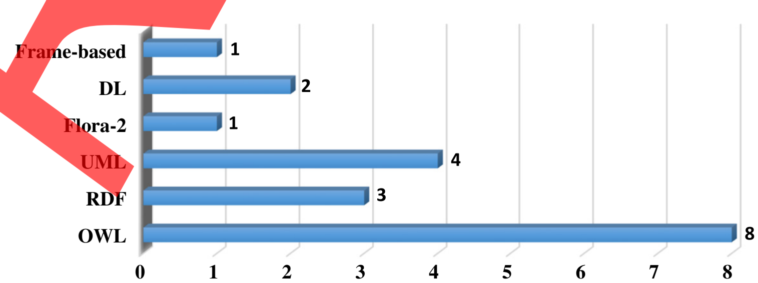

Fig. 9 Used languages in designed ontologies.

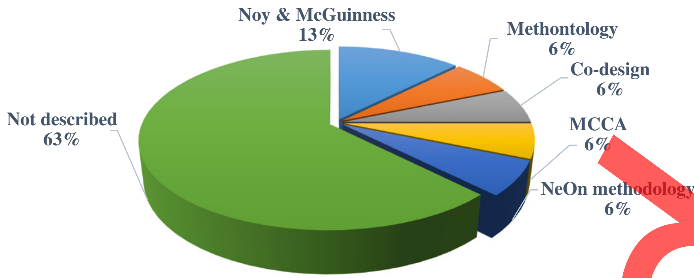

Fig. 10 Used methodologies.

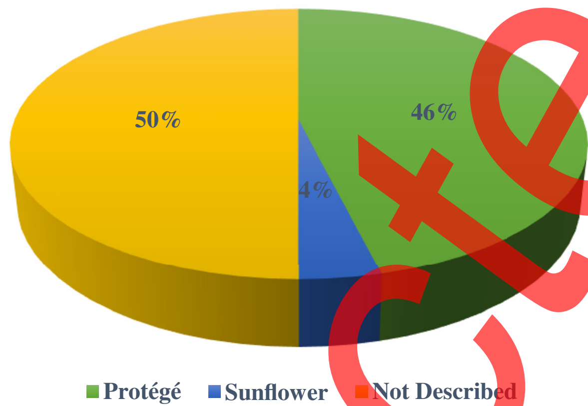

Fig. 11 Used tools.

63% of ontological designers design their ontologies without using any methodology. However, the most adopted methodologies are Noy and McGuinness 13%, followed by Methontology, NeOn Methodology, codesign, and MCCA with 6% each.

5.5 *Tools*

The utilized tools of designing ontology are summarized in Fig. 11. It is obvious that there is not much variety of editors, with Protégé being the most cited (46%). Most studies use this tool for reasoning, a function that is provided by default by a variety of reasoner engines such as FaCT + + and RACER. These engines enable inference of logical consequences from included axioms.[13] Other studies use the Sunflower as library, with many tools that work with the Flora language. Surprisingly, half of ontological engineers have not used any tool to develop their ontologies.

6 Discussion

Most ontologies that have been developed in VRT are for capturing and representing training scenarios or learning contents in the form of an ontology and separating domain knowledge from operational knowledge. The represented scenario, on the one hand, should be described in a semantic and coherent way. Ontology as a tool assists with semantically and explicitly describing the sequence of events, tasks, and information for training scenarios such as storytelling or story lines, for example.

However, thinking about clearance, semantic expressiveness naturally leads us to think about the used methodology and modeling language. We cannot confirm the effectiveness of this role due to all studies using inadequate languages and 63% of studies not applying the methodology, while the rest either misuse the exciting methodology or utilize immature ones. In addition, the involvement of domain experts is an essential part for knowledge acquisition; any lack of key experts can result in a highly partial model.[21] In this study, the consultation with domain experts is only indicated in seven studies. With all of these in mind, using this role under the current conditions will definitely produce a poor model with lack of expressiveness, truthfulness, and details.

On the other hand, separating knowledge from both the system and domain is essential. This role enhances the reusability of the body of knowledge across drivers of systems design. Unfortunately, this approach is inadequate because the majority of studies are for specific purposes, only representing domain ontology. This role should be supported by separating upper ontology from lower ontology. Using top ontology would increase the vocabularies and limit the difficulties in extending or integrating with existing ontology. However, the majority were not designed based on existing ontologies or promoted to be used in other work. In fact, only two papers (see Table 8) reused ontology specified by other designers, and three other papers had their ontology reusable for further design. Reusability is one of the distinguished roles in the ontology domain that can drastically minimize the effort and time for building new learning scenario models. Considering this benefit is highly promising to speeding up the development of VRT processes and simultaneously reducing the cost. Therefore, the proposed ontology design should be built in a way that it can be used across training domains.

Benferdia and his colleagues' work[62] indicated three limiting factors that obstruct the adoption of VRT in ophthalmology: lack of guidance, complexity, and unknown duration of training (needed to achieve proficiency). Basically, users might be lost when entering a VR environment. They need to have explicit knowledge regarding the VR training that they intend to use. Thus, the majority of works attempt to create fitted learning scenarios that fill the needs of the trainees. Providing guidance on disassembling and assembling a rifle[47] and describing and designing a guiding procedure in a way to be used in VR[40] are some examples of how ontology plays a guiding role in facilitating the VR environment. Although only two reviewed studies claim the previous points, they still have a lack of evidence for many reasons. First, none of them takes the benefit of ontology's role such as enhancing communication among stakeholders or applications by sharing a common understanding. This role is very crucial because any missing knowledge or wrong understanding of the domain can result in major costs and time and make a system more complex. Second, the languages and methodologies used are deficient and not enough to capture, represent, and structure explicit knowledge (see Figs. 9 and 10).

Although all of the included studies proposed ontology, 50% of these studies did not make any clear mention about which kind of tool they utilized for designing purposes. Similarly, 63% did not clarify the methodology applied to help design ontologies in the engineering field (see Fig. 10). Misusing or missing methodology in the design process definitely produces complex ontologies. Almost half (46%) of the studies indicated Protégé and another 4% mentioned using Sunflower as editing tools to represent ontology knowledge. Having a missing tool in 50% of ontologies may be attributable to the majority not being heavyweight ontologies that represent data of knowledge with added reasoning or inference mechanisms. A well-established ontology development methodology and tool are essential to the design of a coherent and cohesive ontology.

To guarantee a high quality for any ontology and achieve interoperability, the domain ontology should be designed based on the foundational ontologies.[63,64] The utilization of foundational ontology gives more benefits and higher quality, and it can help reach semantics and facilitate the creation of interoperability models. This is because the upper ontology gives the foundation of a skeleton of knowledge in the domain. However, there is a lack of ontology applications in VRT that were developed based on upper ontology (foundational ontologies), except for ontologies such as PRESTO ontology that follow DOLCE as a foundational ontology. Although DOLCE is a well-known foundational ontology, it was found that this upper ontology and others are ontologically incomplete.[65] Therefore, it is difficult to confirm the quality and interoperability of these kinds of ontologies because many are designed without foundational ontologies, whereas the rest are developed with deficient foundational ontologies.

Endurants and perdurants are other important entities in designing an ontology. In this review, 12 studies mentioned the use of these components together. However, the rest of the ontology applications developed in the VRT domain did not utilize the benefit of these entities. Five of them only focused on endurant knowledge and missed capturing perdurant knowledge. For instance, in VRT in the ophthalmology domain, particularly in cataract surgery application, endurants capture knowledge about "know WHAT," e.g., the iris, cornea, pupil, and so on, whereas perdurants capture knowledge about "Know HOW," e.g., all steps on how to perform cataract surgery. Thus, designing the ontology that only depends on the knowledge of what an eye is all about is dangerous and brings high risk to the patient. For VRT, ophthalmology trainees need to know how to explicitly handle surgery with more details. This will enable them to practice patient management and train them against medical errors in a safe environment. Dealing with human eyes is sensitive, and any trivial conflict with slender ocular tissues can lead to blindness. Therefore, perdurants in this case are more significant to specify the existing knowledge along with endurant knowledge.

Although many authors claimed that perdurants, including process, rules, and events, were covered in their ontology, the majority of these 12 papers applied RDF or OWL or both as their implementation language (see Fig. 9). Both of these languages are not favorable as it is reported that RDF and OWL are languages used to represent the static aspects of the domain. However, OWLS is the only one among the semantic web languages that has the ability to represent a dynamic aspect of the domain because it contains the process model. On the other hand, only one paper used activity diagrams to represent the process or action taking place in VRT. Although activity diagrams have a long future of success in adequately representing activities, this kind of language failed to reach its target to represent a conceptualization of domain interest in an expressive way. Nevertheless, there is a strong need for an alternative and comprehensive language.

The ontology representing language is a significant key component in ontology engineering as well. As shown in Fig. 9, almost all papers that proposed ontology in this review used RDF or OWL or both as modeling languages to represent the ontology. This includes the four languages, which consist of DL, frame-based, and flora. For example, DL is the basis of OWL, whereas the root of flora is OWL. The reaming language is similar to object-oriented languages. Despite all of these languages providing designers with taxonomies or partonomies to build their conceptual models, they unfortunately offer no support with regard to helping designers select a specific structure to build elements for domain interest. At the same time, there is no guideline to justify selecting a particular structure over another. In addition, these semantic web languages are deficient in solving many problems related to semantic interoperability.[66] Four papers, on the other hand, utilized UML as the modeling language. UML has more than nine types of diagrams. UML activity is one of them; it is an expressive language that helps represent human activities. Although UML is the most popular language used among the other languages, along with OWL, ORM, and ER/EER, it fell short in providing users with suitable sets of modeling concepts for representing their conceptualization of domain interest in an explicit and accurate way.[31,67]

The reasoning process is about deducing additional truth about the concepts and relationships that are represented in ontology. This mechanism is one of the promised purposes in choosing ontology. It is further the main reason for designing ontology-based applications. The descriptive language used for designing ontology commonly specifies the inference rules such as first-order predictive logic language.[68] The semantic reasoning is commonly defined using both the language and tool. For example, Protégé is the most used in this study, and it provides by default a variety of reasoners engine, such as FaCT ++ and RACER.[13] These engines enable inference of logical consequences from included axioms; in the same manner, they enable distinguishing the structure's complexity as has been applied in ontology. This structure, hence, specifies ontology's type to be either lightweight or heavyweight. As discussed earlier, more than half of the ontologies in this study missed the use of a reasoning mechanism. The rest used Protégé editor with OWL language. This editor is extended by adding the OWL Plugin that helps edit OWL ontology and gain access to DL reasoned.[69] Having reasoning in ontology, unlike lightweight ontology, adds power to ontology to deduce new concepts based on existing ones. Therefore, the use of Protégé and OWL has the potential for building reasoning or semantic web applications. However, this language, as mentioned, has many philosophic problems and is not truly ontological.

According to Fig. 7, only six papers adhered to their proposed ontology with reasoning. However, this mechanism is missing in almost 62% ontologies in this review. This indicated that they only use traditional structure for representing ontology. In addition, the majority of these ontologies apply OWL as representation language along with Protégé tool. Although this language has been designed to reach the level of automatic reasoning for computational efficiency,[70] many philosophical problems, as reported by Refs. 31 and 66, need to be considered when selecting this language for conceptual modeling language. The main reason for having inference and reasoning in this study are to empower VRT to provide decision making, evaluate trainee competency, pose feedback, query and retrieve information, etc.

To the best of our knowledge, the ontology applications that were developed for VRT are still limited and not well explored in ontology and VRT literature. This area of research is still immature, and there is still no proper understanding on how ontologies can support VRT. This review systematically helps present the state-of-the-art ontologies for VRT. However, it is too larger of a scope to look into ontology for VR in general because ontology is designed for a specific purpose of the application domain, such as in this case is VRT, which is what we have decided to focus on. In this sense, a variety of roles were exploited in designing ontology for VRT including reusability, enhancing communication, capturing and structuring training scenario or learning content, separating domain knowledge from operational knowledge, providing guidance in VE, providing reasoning process, and enhancing interoperability role. Only two roles, capturing and structuring knowledge and separating between domains, are mostly used to facilitate VRT design, whereas the rest are scarcely employed. In addition, ontology was missed or misused for incorporation in all design phases of VR methodology.

Over and above these shortages, it is difficult to guarantee the explicitness, generic, unambiguity, and truthfulness of training and learning scenarios in VE that the proposed ontologies attempted to represent. All of them applied deficient foundational ontologies, languages, and methodologies when designing ontologies for VRT; additionally, they frequently either misrepresented or inadequately described perdurant knowledge. This could consequently breed high hazards in real life, especially when VRT is for areas involving trivial details that are important for saving lives. These sectors may include emergency response, healthcare, industry, and the military.

Therefore, the designed ontologies for VRT are not yet ubiquitous. There is thus an urgent need to address all of the above gaps. The next section gives some promising directions and guidelines on how to handle the raised issues.

7 Conclusion and Recommendation

The aim of this systematic review is to answer the following questions: (1) what are the ontology roles that are used to facilitate VRT development? and (2) what are the design components that are used in designing an ontology for VRT development?

Regarding the first question, this review gives us a possibility to identify the fundamental roles of ontology that are used to facilitate VRT development (see Table 8). Although many useful roles are applied to design the ontology, only two roles (i.e., capturing and representing training scenario and separating between domains) are frequently used to facilitate VRT design, whereas the rest are rarely utilized. In addition to the striking lack of usage of fundamental roles and ontology in all VR's design phases, it is difficult to confirm the high quality, semantics, unambiguity, and interoperability of reviewed ontologies because of the reasons elaborated in the discussion section. To do this, an ontology should be designed based on key components. This refers to a third question.

First, for designing a domain ontology mainly for supporting knowledge-intensive tasks such as VRT, the ontology must be designed under a common upper ontology, such as UFO and DEMO-design engineering methodology for organization. Using a complete foundational ontology is the backbone of designing an ontology, whereas the use of upper ontologies in this review is ontologically incomplete and is deficient of foundational ontologies. Second, utilizing high explicit modeling language (e.g., OntoUML and UML based DEMO) is considered significant due to most applied languages being deficient and not enough to capture, represent, and structure explicit knowledge. This makes VRT more complex, costly, and time consuming. In addition, perdurant and new methodology are key features as well. Designing ontology, for example, only depends on knowing what is existing (endurant); it is dangerous and brings high risk, particularly in some domains such as health, industry, and military sectors. In ophthalmology, for example, the trainee needs explicit details on how to conduct surgery during VRT because in real life, even a trivial mistake with slender ocular tissues can lead to blindness. Similarly, existing methodologies have not been widely recommended to be a standard upon which to build an ontology due to the absence of studies that justify the best methodology for developing an ontology.

Designing an ontology for VRT needs an established ontology development methodology under a well-researched methodology such as design science research methodology (DSRM). It is a problem-solving research paradigm that is aimed at designing artifacts as a solution to research problems. It is further claimed that ontology development is compatible with DSRM. Therefore, to have the lens of DSR into ontology design is a fruitful idea.[61,71,72] As a result, Ahmad et al.[57] recommended a new methodology that can be flexible and generic. In the method, ontology development methodology is rooted in DSRM according to DSRM's design and development, demonstration, evaluation, and communication activities. It was successfully used to generate OntoWM for the waste management industry. Although this methodology helps cover the existing deficiencies, we do not claim that it is the best available practice. More research is required to achieve a unified and standard methodology. Finally, a variety of roles should be taken into consideration throughout all stages of VRT design, with this tool being the main guidance to facilitate VR development. These roles include reusability, enhancing communication, capturing and structuring training scenario or learning content, provide guidance in VE, separating domain knowledge from operational knowledge, facilitating reasoning process, and enhancing interoperability role.

This study helped indicate the appropriate and critical design approaches that should be considered when designing an ontology for VRT. These approaches can assist in effectively building VR training scenarios and enhancing student learning by capturing and representing expert knowledge in sequence and in a coherent manner. Thus, the ontological engineer should take into account the directions provided to make the right choices for the more convenient upper ontology, modeling language, methodology, and roles. Consequently, this will lead to the fulfilment of user requirements, while knowledge bases are ideally captured, visualized, communicated, reused, and shared in a consistent, generic, and unambiguous manner. Accordingly, the proposed design elements and roles for developing ontology can demonstrate potential abilities to address the semantic and expressiveness of learning content, enhance interoperability, promote the reusability of training scenario, and facilitate the development process of VRT.

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