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A NOVEL ONTOLOGICAL APPROACH TO MODELLING ENGINEERING PROCESSES: A COUPLED TANK SYSTEM CASE STUDY

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ABSTRACT

Many modelling techniques such as Artificial Neural Network (ANN) and SIMULINK have been employed in engineering processes such as control systems. However, these techniques lack some beneficial features such as the auto-classification and self-awareness of knowledge, the dynamic knowledge discovery, validating the consistency of knowledge and the possibilities of embedding Semantic Web Rule Language (SWRL) rules into various modelling tasks.
This paper presents an original and innovative ontology design that models the coupled tanks system (CTS) with additional capabilities of providing aforementioned advantages.
This new approach for modelling engineering phenomena employs the Web Ontology Language (OWL) and also processes the capabilities of incorporating Description Logics (DL) and Semantic Web technologies into the ontology-based design. The results obtained in this paper show the successful demonstration and implementation of our new knowledge modelling approach.

Keywords: Coupled Tank System (CTS), Semantic Web Rule Language (SWRL), Web Ontology Language (OWL), Modelling, Ontology, Semantic Web Technology.

1 INTRODUCTION

It is a common practice in industry to have a prototype of a process to enhance system reproduction, acquire knowledge or perform necessary simulations (Christova et al. 2003; Zhao et al. 2013). This is made possible by first designing a model of the process or system. Models are required to predict the behaviour trends of systems and they are very important in many situations where it is either inconceivable or impractical to produce experimental conditions in which scientists can directly determine the outcomes of events. Modelling is the process of fully representing and understanding the dynamics of the plant so that it can be a substitute for the real plant.
In reality, the majority of the process plants are generally nonlinear in nature. Many of the inherent physical processes are entirely unknown (Gupta & Verma 2012) and this thereby makes modelling very significant. A good model representation of a process is important in order to be able to perform many useful tasks. The coupled tanks system (CTS) case study is used as the plant and it is discussed further in the next section.
There are numerous available modelling approaches and more methods are being progressively discovered over the years. In most of the cases, the use of a particular modelling technique for a particular task depends mostly on its practical application. A few examples of model types with varied advantages includes: statistical models, deterministic models, conceptual models, and mathematical models. In most designs, linearised plant models are commonly used due to the difficulties in deriving nonlinear models (Murray-smith 2012). However, linearised models are prone to errors owing to various techniques involved in the process of linearisation. Some assumptions are made during this process that reflect the features and characteristics of the system and these assumptions might invariably lead to a degradation in the performance of derived models.

There are however some shortcomings of the above mentioned modelling techniques such as the inability and bottlenecks in obtaining accurate model representation of the process. However, this approach has the capabilities of employing embedded semantic web technology and Description Logics (DL) by using Web Ontology Language (OWL).

In view of these limitations, this research work presents the use of a novel approach and focuses mainly on modelling of nonlinear tank dynamics. This involves the use of ontology and the semantic web technology. It involves acquiring and analysing domain knowledge in the subject area. Secondly, following knowledge acquisition an ontology model of the domain, based on semantic web technologies, is constructed. With this new concept, the model can be adaptively created and suited for varied dynamics. The concepts in this work can be extended to many engineering processes. OWL language has been applied previously in the manufacturing sector (Li et al. 2009; Li et al. 2011). Li et al. (2011) have designed a semantic annotation framework called OntoCAD for supporting multiple engineering viewpoints by using OWL representation and DELPHI. On the other hand, our proposed work uses OWL for knowledge engineering process with its top layer Semantic Web Rule Language (SWRL) for mathematical calculations. The benefit of this approach is that the machine can still be able to perform reasoning over mathematical equations besides the encapsulated knowledge in ontological form.

Another important factor in our new approach is the fact that the data model is inherently open-ended. This implies that new data and new relationships can always be easily incorporated within the model. There is a need to facilitate automated inference and make intelligent information discovery by expressing constraints and relationships (such as cardinality, transitivity, disjoint, domain and range restrictions). Moreover, the CTS will be described using entities and objects with formally well-defined semantics.

The remainder of this paper is organised as follows: Section 2 examines the existing modelling approaches used in the CTS. Section 3 introduces the modelling process using OWL and SWRL. The methodology for the modelling processes are provided in Section 4 while the research results and advantages derived from this approach are analysed in Section 5. Finally, we draw the conclusions of our research work in Section 6.

2 COUPLED TANK SYSTEM MODELLING REVIEW

The Coupled Tank System (CTS) is a very important piece of equipment that can be used to study the dynamics of fluid flows mechanisms in tanks (K. Owa et al. 2014; Kayode Owa et al. 2014). A simple schematic diagram is shown in figure 1. There are two inputs, voltage of pumps 1 and 2, and there are two outputs referring to the height in tanks 1 and 2. Further descriptions of the working principles can be obtained from cited literatures (TecQuipment 2013; Mohideen et al. 2013; Kayode Owa et al. 2014; K. Owa et al. 2014).

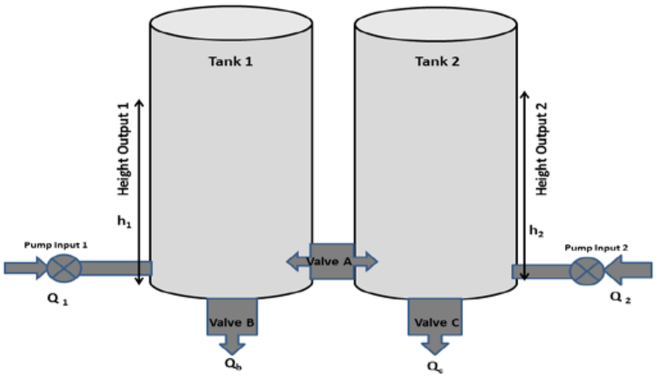


Figure 1: A simple illustration of CTS

Much research work has been carried out especially in the areas of modelling of the CTS (K. Owa et al. 2014; Kayode Owa et al. 2014, Hu et al. 2012, Echaieb et al. 2012; Senthilkumar & Lincon 2012; Kousar et al. 2012) using techniques such as Artificial Neural Networks, SIMULINK and linearised forms of the fundamental equations. All of these methods generate solely a numerical solution to the outputs of the model. However, further incite can be obtained using novel knowledge engineering approaches.

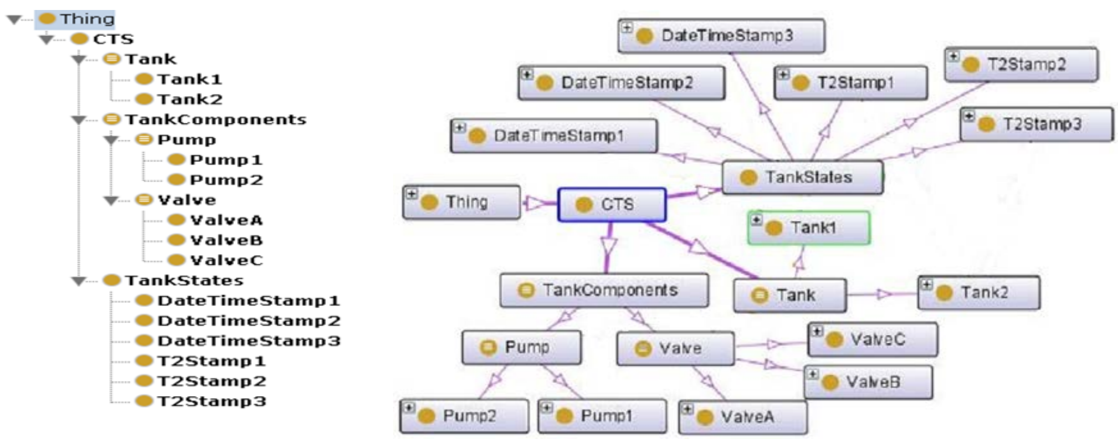
In this research work, an innovative scheme towards modelling engineering processes is presented using ontology and semantic DL rules, yielding both knowledge dynamics and numerical outputs. The rest of the sections in this paper describe our novel approach to modelling using the CTS as a case study.

3 OWL AND SWRL

The OWL (Grau et al. 2008; Ding et al. 2007) is a Semantic Web Markup standard for publishing and sharing ontologies on the world wide web. This formal representation supports defining explicit concepts, roles, constraints and restrictions, which are closer to human expertise. The OWL Lite, OWL DL and OWL Full (Horridge et al. 2004; Wang & Feng 2013) are three sub-languages of OWL. The ontologies are created and edited by using different constructs (such as classes, properties and individuals) of OWL representation. The OWL classes (Horridge et al. 2011) are used to interpret the concepts of the knowledge domains by combining the `class descriptions' and `class axioms'. The class description consists of named and unnamed classes (Horridge et al. 2007). The `Thing' is a predefined named class and all the classes defined in the knowledge-base are its subclasses while the "Nothing" class represents the empty set of objects. A restriction added in the named class indicates an anonymous superclass. Such classes are formed from logical descriptions and contain the individuals satisfying the logical descriptions. The AND ($\cap$), OR ($\cup$) and NOT ($\neg$) Boolean operators are used to construct the logical descriptions. The restrictions along properties describe the sets of individuals in terms of the types of relationships in which the individuals participate. For instance, the universal restriction, $\forall$, along the specified property describes the individuals that have all values from the filler class. The cardinality restriction (i.e. Minimum or Maximum or Exact) describes the sets of individuals in terms of the number of relationships that the individuals must participate in for a given property. The Subclass axioms, Equivalent class axioms and Disjoint axioms are all different types of OWL axioms. The OWL properties (i.e. Object Properties, Data type Properties, and Annotation Properties) are binary relations. The real-world objects are called individuals. An individual can belong to one or more classes. For example, the `Audi' instance belongs to `Car' and `Vehicle' classes. SWRL (Martin et al. 2005) is a top layer of OWL in the semantic web layer architecture. It helps to perform mathematical calculations over the ontological represented knowledge.

4 CTS MODELLING USING SEMANTIC WEB TECHNOLOGIES

The CTS model is designed by using Semantic web standards (OWL and SWRL). The designed, novel CTS ontology model has three classes (Tank; TankComponents; and TankStates). Figure 2(a) illustrates the hierarchical structure while figure 2(b) shows the graph structure of the CTS Ontology Model.



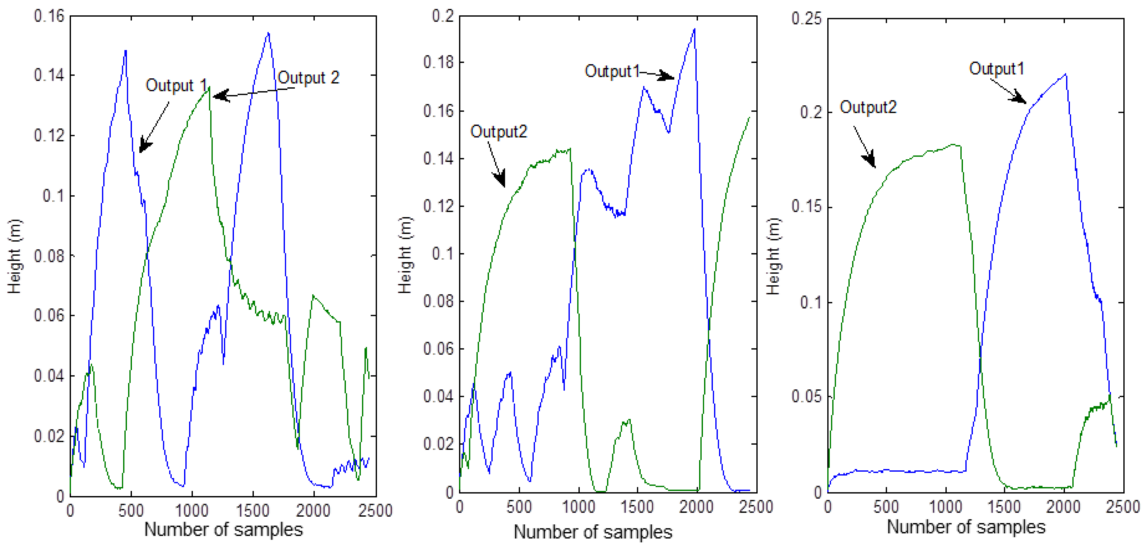
(a) Hierarchical structure (b) Graph structure

Figure 2: The CTS Ontology Model

The 'Tank' class represents an abstract structure of a tank and provisions can be made for more than one tank (two in the CTS, Tank1 and Tank2). The 'TankComponents' class keeps the information of all the tank components. The instances of this class are associated with the instances of the Tank class by using OWL object properties. These object properties are as follows: "hasPump", "hasState", "hasValve", and "isStateOf". Finally, the 'TankState' class of the model is responsible for keeping the various real-time states of the tank(s). Each state represents the specified height, time stamp and also keeps the reference of previous and future state (if exists) of a tank under consideration.
In addition, the SWRL supports the proposed ontological approach with the inclusion of the mathematical equations.

5 RESULTS AND ADVANTAGES OF THIS NOVEL APPROACH

Three different data sets each of 2,445 samples of voltage measurements were collected from real open loop practical experiments on the multi-input multi-output (MIMO) coupled tank system (K. Owa et al. 2014; Owa et al. 2013). These data are used as inputs for the designed CTS ontology model and the results of the model outputs (height measurements in Tank 1 (Output 1) and Tank 2 (Output 2)) are presented. Figures 3(a), 3(b) and 3(c) are the corresponding model responses obtained from the ontology model when subjected to the three different test data respectively. The CTS ontology model outputs of figure 3 show the successful demonstration and implementation of this novel approach in terms of the numerical outputs, matching those from traditional methods.



(a) Test data 1 (b) Test data 2 (c) Test data 3

Figure 3: Ontology model responses from raw experimental data

The additional contribution of using this novel technique is elicitation of knowledge engineering. The CTS ontology model provides many modelling benefits that cannot be obtained in other traditional modelling approaches. These advantages are highlighted below:

5.1 Auto classification and self-awareness of knowledge

Conventional computer languages support merely computations and calculations but the OWL representation assists in self-awareness and inferencing with the required resource knowledge. The formal description of the features and components of the tank are defined in the form of class constraints in the CTS ontology. Such constraints enhance the self-awareness and understanding of machine and support accurate classification and categorisation of knowledge. For instance, a real world object is defined as subclass of the Tank class that keeps certain features of components. In such case, if it has association with the Valve A and Pump 1 (which are the components of the Tank 1) by using OWL properties thus the OWL classifier auto-classifies it as an instance of the Tank 1 class.

5.2 Dynamic discovery of knowledge

The CTS ontological knowledge-base provides a dynamic discovery of knowledge. Various states of tank represent the height of the liquid and associated time slice can dynamically be retrieved by calling DL queries. For example, the query ∃ hasState . state99 can infer all the previous states of the specified tank. The next state(s) can be visited and examined by using certain identical DL queries. Such dynamic discovery of knowledge can support the visualisation of the knowledge which invariably is sharable, modifiable and reusable within diverse application contexts, such as fault detection in the CTS.

5.3 Validating the consistency of the knowledge

The knowledge consistency of the CTS knowledge-base can be validated by using the OWL-based reasoner. For example, the limit n liquid range of the tank is defined in the Tank class. Such a constraint helps in validating the correct liquid height of the tank. For example, if an object of the tank has liquid height of 0.30 or more then the reasoner would classify it under the Nothing class, shown by the dotted inference lines in figure 4. The data range of the knowledge is compared by the constraints, (∀ hasHeight . double[>= 0.0]) ∩ (∀ hasHeight . double[<= 0.25]) , of the Tank class as shown in figure 4. This constraint supports the OWL reasoner in checking and verifying whether the given real height is within the range.

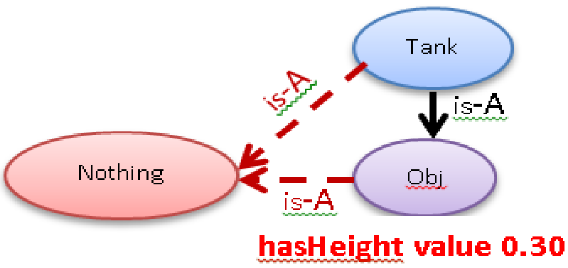


Figure 4: Knowledge-based validation process

6 CONCLUSIONS

A novel approach for modelling engineering processes using a coupled tank system as a case study has been presented in this research work. This proposed ontology-based prototype system demonstrates a seamless approach to modelling CTS laboratory equipment with clearly mentioned advantages over the rigid computational methods, mainly SIMULINK.

This new technique provides additional functionalities with added advantages to modelling engineering domains. Some of these merits include auto-classification and self-awareness of knowledge, dynamic knowledge discovery, validating the consistency of the knowledge and the possibility of embedding SWRL rules into the CTS Ontology. Increasing the complexity of the CTS, with increased number of inputs and outputs, could be facilitated with this novel method. This could lead to lengthier timings for output production however it is not foreseen to be a problem. Future work can be extended to ontology design concerning the optimisation and control strategies for other engineering processes.

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