Ontology based Semantic-Predictive Model for Reconfigurable Automation Systems

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Abstract- **Due to increasing product variety and complexity, capability to support reconfiguration is a key competitiveness indicator for current automation system within large enterprises. Reconfigurable manufacturing systems could efficiently reuse existing knowledge in order to decrease the required skills and design time to launch new products. However, most of the software tools developed to support design of reconfigurable manufacturing system lack integration of product, process and resource knowledge, and the design data is not transferred from domain-specific engineering tools to a collaborative and intelligent platform to capture and reuse design knowledge. The focus of this research study is to enable integrated automation systems design to support a knowledge reuse approach to predict process and resource changes when product requirements change. The proposed methodology is based on a robust semantic-predictive model supported by ontology representations and predictive algorithms for the integration of Product, Process, Resource and Requirement (PPRR) data, so that future automation system changes can be identified at early design stages.**

Keywords- knowledge-based system, semantic technology, reconfigurable manufacturing systems

I. INTRODUCTION

Due to frequent product changes, design and reconfiguration of manufacturing systems is one of the fundamental challenges faced by the manufacturing industry. Current engineering approach including complete sets of methods, models and designs covering entire lifecycle are mostly fragmented and have not met requirements of product lifecycle management [1]. In fact, product, process, mechanical and control engineers need to carry out a number of design change loops to finalise product and manufacturing system design.

To reduce the time to market and risks, a number of digital modelling and simulation tools are adopted by industry to visualise, validate and optimise manufacturing system before physical build. However, for quick iterative design, these tools lack reuse of existing knowledge and data from product, process and resource domain due to the lack of strong data coupling, such as content coupling, common coupling and data coupling. Some software share editable resources but details may lose during the data conversion. Usually a huge amount of data cannot be shared or transferred among different systems [2], which results in the use of labour-intensive and ad hoc methods for data sharing across different engineering domains.

Many previous studies have reported the increasing use of data modelling tools to enable reuse of data across different engineering domains. However, knowledge management and reuse in a systematic manner does not exist to support reconfiguration of manufacturing systems when product requirements change [3]. Using existing digital modelling tools, modification of simulation model to accommodate changes can result in a significant cost and time. This is because substantial knowledge and experience is required to understand interdependence of product, process and resource changes to carry out system reconfiguration [4]. In addition, existing digital modelling tools are complex to use as they require a wide range of technical skills and manual work.

In this paper, the authors address the gap between product, process and resource modelling by automating the changes in the 3D simulation models based on the changes in the product requirements. A semantic-predictive model is proposed to enable knowledge-based mapping of PPRR data to eliminate the need for specialist human knowledge and experience to carry out manual changes in the simulation models of manufacturing systems.

II. LITERATURE REVIEW

A. *Current Frameworks for Integrated Manufacturing Systems Design*

Integrated manufacturing systems design aims to establish a collaborative platform using various analysis and design methods for a concurrent and coherent solution. Using existing engineering approaches, such as concurrent engineering, factory designers consolidate and simplify design methods to improve manufacturing systems design during the early stages of product design and assembly planning [5]. However, a number of challenges still need to be resolved, such as longer design cycles, cost and inconsistencies in models. Generally, traditional engineering methods are intended only for particular issues and tasks, and are based on unique knowledge expressions, models of products and process sequences [6]. In order to integrate various domain-specific engineering tools with an interactive platform to reduce product design lifecycle and cost, some integrated manufacturing system framework are used for facilities sharing, data transfer and designers communication. For example the Virtual Factory Framework (VFF), the Sustainable Factory Semantic Framework (SuFSeF) and The Open Group's Architecture Framework (TOGAF) are the most influential architectures for manufacturing systems integration for Product-Process-Resource (PPR) domain [7-9].

VFF is a framework to integrate process and resource information into a shareable virtual environment, while supporting manufacturing planning design for whole product lifecycle [10, 11]. The key aspect of VFF architecture is a Virtual Factory Data Model (VFDM) based on the semantic technologies to define various types of data and knowledge stored in a shared knowledge repository using a universal language. However, the VFF architecture cannot handle complex control logic for characterising manufacturing systems. Moreover, a large number of applications are added into the framework via a specific connector which provides a connection between different platforms and supports data conversion. In such an approach, connector design seriously affects the efficiency of integration and the systems may crash due to the disconnection.

SuFSeF (Sustainable Factory Semantic Framework) developed a specific middleware that requires input/output data conversion and transfer from the original database to the shareable data warehouse of the virtual factory platform. Terkaj, et al. [7] stated that the SuFSeF expands the VFF and optimise the architecture of factory design and management. SuFSeF adds an integrated middleware between digital factory tools and data repository to support data layer integration using ontologies. However, only an architecture is provided without defining individual model structures which are required for PPR integration. After obtaining access control, data query is executed at the data presentation layer which is able to acquire the knowledge-based feedback using semantic logic system.

TOGAF is an industry standard method to design manufacturing systems, and it consists of four levels to control manufacturing information technology architecture, i.e. design, plan, implement and management [12, 13]. Based on the advantages of TOGAF, factory system design methods and models are key drivers in the integration of different levels of industrial processes. However, concurrent engineering was not considered in the concept of enterprise continuum and the related semantic technologies were not implemented in this framework.

B. *Semantic Formalism*

Most knowledge-based systems are dependent on sharable design warehouses and ontologies, which formalise data structure and relationships. Goel, et al. [14] indicated that the use of machine learning techniques and multimodal reasoning could help support a wide variety of design methods and behavioural models.

Several automation systems have been built with semantic data analysis tools [15]. For example, GATE (General Architecture for Text Engineering) API is a famous development tool to support information collection from different data sources and provide a basic processing resource for information extraction called ANNIE (A Nearly-New Information Extraction System) [16]. Moreover, ANNIE contains a variety of natural language processing techniques to analyse information based on semantic rules, such as gazetteer, NE transducer, POS tagger, English Tokeniser, OrthoMatcher etc. [17].

Jong, et al. [18] used a three-tier architecture involving a historic knowledge platform, built-in API and MS-SQL database management system to support mould design. Also, a demand-driven knowledge acquisition system based on demand pre-processing, knowledge retrieval and searching is reported in [19].

C. *Ontology-based Predictive Rules*

Ontologies have been used by a number of researchers to integrate product with manufacturing processes and resources. According to Hernández-González, et al. [20], ontology provides a standardised, formatted and structured knowledge description, with the benefit of being shareable and reusable. In general, ontology is useful as a key technology to extract and integrate factory systems design data from design software and their database [21].

Using ontology rules, knowledge-based systems can be established to support the retrieval of product design concepts. However, retrieval cannot fulfil all the requirements of factory system design. For example, currently product designers do not get real-time reports about available resources during the design phase. Hui, et al. [22] mentioned semantic technologies, which provide and process data from different customers or departments, offer an opportunity for creating ontology-based predictive systems in order to establish a real data-based semantic-predictive system. In addition, based on semantic modelling approach, product information modelling is developed and applied in assembly planner for obtaining the necessary product information and helping process design [23]. Despite the increasing number of semantic tools and development of structural models, this area still faces a number of challenges, such as process prediction and appropriate resource selection during product changes.

III. PROPOSED FRAMEWORK FOR MANUFACTURING SYSTEMS INTEGRATION

A. *Objectives of the Framework*

A common engineering understanding is that products (P) are realised by processes (P) which consume resources (R) and requirements (R). To model the interdependencies to predict the impact of changes, there is a need to understand process, resource and requirement implications of product changes and vice-versa. The rapid reconfiguration of systems depends on the specific domain knowledge which can be reused to facilitate machine learning, expanding semantic database and building new product modules with short product development cycle. For the PPRR model, each module's knowledge is independent and stored in the corresponding storage space.

Fig. 1 shows a framework of the ontology-based semantic data integration including PPRR data transformation, semantic database with ontology mapping and rule-based predictive model. This framework support reconfiguration of an existing simulation model. The semantic translation model translates simulation model of an assembly system to semantic data that can be uniquely recognised. After mapping semantic data with ontology, product data is linked to process and resource data. Thus for each change in the product model automatically links relevant process and resource data. During product requirements change, rule-based predictive model modifies PPR semantic data and update XML file (simulation model) automatically. As a result, required changes can be carried out in the simulation model without manual modifications.

Each knowledge system contains a specific set of contents, including process plan database, available resource data and product model knowledge. For example, a product model contains process knowledge, which can be found from the previous process design library. Moreover, resource knowledge, which is generated by the established resource models, contains process models and vice-versa. All knowledge can be retained by the inherited methods, and knowledge can be enhanced by updating iteratively using factory system modelling science. Rapid reconfiguration is not just re-combination of the old model, but also the generation of new products, processes, resources, and requirements based on previous knowledge.

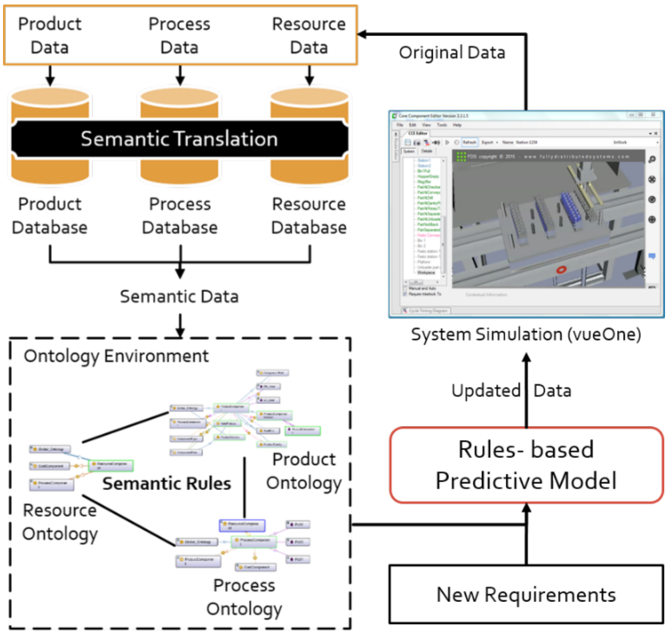

Fig. 1 Ontology-based Semantic Data Integration Framework

Based on a cross-platform systems integration requirement, the framework can analyse an entire production process plan and evaluate its suitability for different products. By splitting production process and process flow analysis, production process can be transferred from a process design software to a process simulation platform. Furthermore, resource and cost information as different knowledge warehouse can also be transferred and combined in other modelling software, such as simul8, aPriori Evaluator and DELMIA Modeller. Digital simulation framework should obtain an appropriate control logic and basic information, as a result, process flow chart is displayed on this platform and can be easily modified to accommodate an unexpected plan. Any software which is connected to this framework is able to automatically update data and system status. However, practical challenges exist when implementing integrated 'Intra or Inter Information Systems'. This is because most of the time, systems are designed without detailed consideration of levels of integration required in enterprises (PPR interconnections), file transfers and data formats needed, levels of manipulations required, specifications and representations utilised. Thus, a semantic transformation model is necessary to maintain correct meaning and suitable formatting during data transformation between different systems.

B. PPRR Data Transformation

As mentioned above, semantic data transformation is an important aspect to increase system reliability, but current process simulation systems cannot analyse data meaning and relationship between product, process and resource. Furthermore, change in product cannot directly reflect process change or resource change. This is because product, process and resource data is stored in database without meanings and relationships. Ontology-based predictive modelling can build the link between different databases and predict sub-link or product design solutions using Pellet and HermiT reasoners. In addition, such modelling requires the understanding of process, resources and cost implications of products changes and vice-versa.

C. Semantic Database with Ontology Mapping

Typically, ontology-based system depends on a specific domain knowledge, but that knowledge cannot be reused to facilitate machine learning via a set data dictionary. To address this, a semantic data model can be used to improve the accuracy of ontology-data mapping and enhancing system robustness. Integrated semantic technology and machine learning algorithms can potentially expand the scope of product design knowledge and improve semantic capabilities for data analysis. Semantic technology can translate designers' questions and customer demands from human language to ontology language, such as OWL/XML or RDF/XML. Furthermore, system server derives available product models, manufacturing process plan suggestions and resource situations via semantic mapping of PPRR configuration libraries.

Semantic modelling usually processes a large amount of data and relationships from the ontology engine. In order to improve the processing efficiency and accuracy of queries, the authors have established separate ontologies to avoid accessing unnecessary results. Each domain ontology establishes independent 'attributes' and the ontologies, which have the same type or similar semantics, share one public contact ontology as a 'relation', such as scenario domain, liaison domain and feature domain. Additionally, queries can be applied at the sub-domain ontology to obtain a specific parameter or the integrated ontology (i.e. different components of the factory system including product, process, resource, and requirement). Through the semantic model, the information is logically extracted and optimised. Furthermore, the end results are displayed through visual models or 3D based virtual modelling tools in order to improve the system design and reconfiguration process.

D. Rule- based Predictive Model

The purpose of predictive model is to build relationships among process-product, process-resource and process-requirement. For example, griper open process is linked to griper CAD model and griper movement sensors. In addition, griper open speed and opening stroke are both included in griper requirements. On one hand, process change directly affects resource planning and requirement. On the other hand, available resource for current automation system also restricts the usability of process design and product design. During resource change, appropriate modifications are made in the process and final product design is directly reflected by process change. Thus, changes in process requirements (ΔProcess) are closely linked to resource changes (Δresource) and the constraint of process requirement (ΔRequirement) is the key for a new product design (ΔProduct).

Another important aspect of the semantic predictive model is the future prediction. Based on the law of conservation of information, this model uses decision tree to predict any available processes and a suitable manufacturing system design model on the basis of requirement change such as cycle time, material and costs. Those parameters are marked with different rank which help prediction system to evaluate all processes according to current available resource.

However, decision trees rely on a hierarchical structure in which data is categorised at various levels to simplify decision-making and calculations become very complicated if different decisions have restriction or uncertain links. A semantic-prediction model can transfer data into a rule-based ontological structure, so system can choose an optimal solution from system ontologies to avoid conflicts. As a result, the predictive model not only predict requirement changes in next phases, but can also determine valid system design which meets the requirements of product.

IV. CASE APPLICATION

A. Battery Cell Assembly

Due to the growing requirement and rapid changes in product technology, battery pack design and manufacturing for electric vehicles (EVs) represents a largely unknown territory for the car manufacturing industry. A variety of battery pack designs are typically expected to be manufactured on a single assembly line to address the changing requirements. As a result, these assembly lines are facing a massive reconfiguration and redesign over a short period of time. For example, the BMW i3 battery assembly line went through major changes three times in the past few years. In such circumstances, a rapid reconfigurable assembly system design approach provides an opportunity to address automatic readjustment of assembly line for different products, including new product variant analysis, assembly line evaluation and assembly system reconfiguration etc.

This case study is based on a Make-Like-Production (MLP) battery assembly line installed at WMG, University of Warwick. This MLP facility aims to mock-up battery assembly processes to configure, integrate, test and evaluate current automation systems addressing reconfigurable assembly system design for frequently changing product, process, resource and requirement. This assembly line is composed of a number of automatic and manual assembly stations.

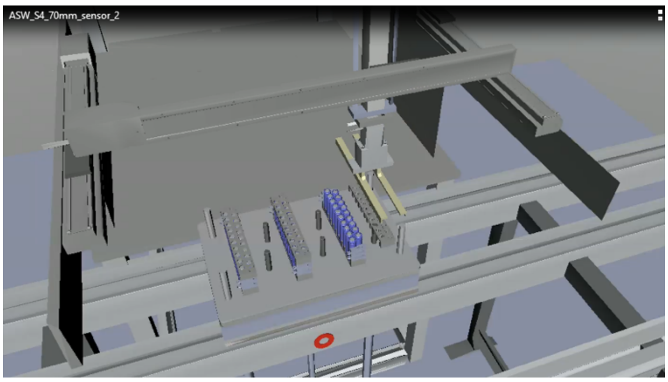

Fig. 2 Pick and Place Station in Simulation Environment

Although current product line is based on a class of products, the assembly line was designed as an efficient scalable and reconfigurable system. A number of modelling and simulation tools, were used to test and evaluate different operating conditions and products requirements to reduce time and engineering costs. However, the existing modelling tools require experienced engineers to complete each revision of simulator. The focus of this case study is to reduce human efforts using an ontology based semantic-predictive model for such system design revisions.

For the case study, a bespoke pick and place station is selected that carry out top plate assembly using a gripper to pick-up and drop-down battery cell plates (see Fig. 2). In this station, there are four sequence checks to determine location and control processes. So the condition of each sequence check is a core step for sequence of operation (Process). An ontology based semantic model is used to transfer the XML file which is an output of simulation system to semantic data and map basic rule for system prediction.

B. Semantic Translation Data

Current data is transported using an XML file between different functions or software, and the data is read using a fixed DOM reader module. To ensure that the meaning of the data does not change by semantic transforming tool, an evaluated ANNIE Gazetteer package is imported into GATE based on DOM reader module in a virtual process planning and commissioning tool vueOne, see [24] for further details about vueOne. The analysis results are represented as data with semantics (see Fig. 3). All information of components, such as Destination Sate, Interlock and Conditions etc., are converted to semantic data using GATE.

For example, StateID (marked in purple) is defined as a state index which is signed as the identity of each process and the meaning of transition includes TransitionID (process sequence number), Origin_State (current state ID), and Destination_State (the following state ID) which decides the process flow in current process. If process order changes, system only needs to modify Origin_State and Destination_State according to the corresponding state ID. Furthermore, state duration time and position could also be changed to a new value based on process changes.

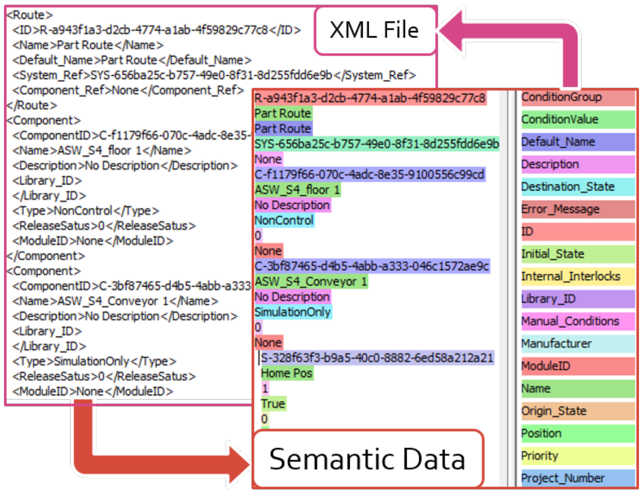

Fig. 3 Semantic Data Translation

The ANNIE Gazetteer package is using UTF-8 encoding and hierarchical classification storage, so it is scalable and transplanted in different operating conditions or environments. The approach can be extended to support design changes in similar manufacturing systems.

C. Mapping with Ontology Dictionary

The global ontology is defined as follows: Business Case, Component Role, Component Type, Process Component, Product Component, Cost Component, Delivery Method, Liaison, Liaison Type, Product Volume, Required Test, Resource Component, and Scenario (see Fig. 4). Ontology dictionary has been used to structure and integrate data so that product, process and cost information can be represented in a structured database and smooth communication can be achieved between each domain area.

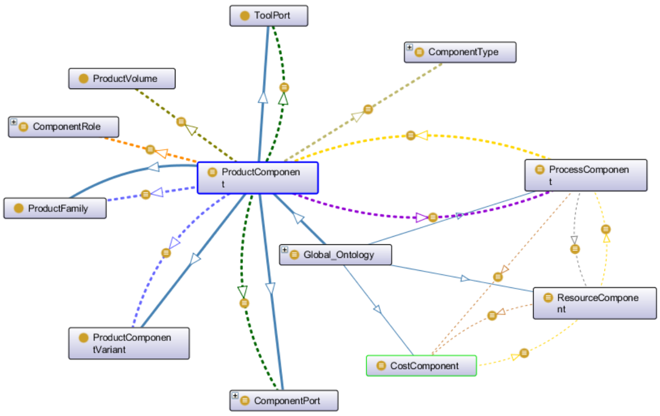

Fig. 4 Product-Process-Resource-Requirement Ontology Mapping

Using ontoRoot plug-in, GATE could process text annotation with classURL, URL and type based on existing ontologies. Moreover, the classic extract information in GATA is based on JAPE (a Java Annotation Patterns Engine) which builds a grammar library using regular expression operators. So JAPE rules are created to recognise related components and link ontologies to control logic document.

After automatic matching of ontologies with semantic data, the data variables of the pick and place station can be flexibly changed without resulting in data inconsistency. In other words, process data is associated with product data and resource information, such as gripper movement can be reconfigured according to battery dimension and plate size.

D. Basic Rules for Prediction Model

Current prediction model can calculate each location of the battery and automatically generate or modify sequence of operation file (XML). Fig. 5 introduces the algorithm logic including product, process, resource and requirements changes. Battery dimension changes may affect cell layout or pallet design. According to the new dimension, batteryLayoutArrangement function calculates a new cell centre point for specific battery cell index and then provides a new place position for the griper movement position (D-Mover Pos 3).

Therefore, existing layout and positioning for each resource were set for an initial state and horizontal and vertical arrangement rule, battery dimension, gripper location link, and cycle time calculation model are configured to update new parameters for simulation XML file.

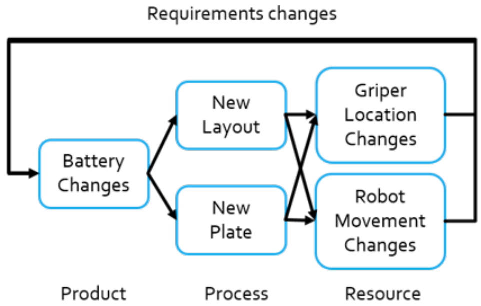

Fig. 5 Prediction Model Algorithm Logic

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//1: Read Width, Height, Diameter of targeted battery as W, H, D from user;
//2: Get "D-Move Pos" state as State1 from battery_cells.owl file;
//3: Repeat the steps until last step in State1
        Calculate battery size and center point using W, H, D;
        If new battery size fits cell pannel Then
                Change State1.Step.Position to new battery center point;
//4: Print out all changes for owl file;
//5: Update owl file via semantic model;
//6: Convert new owl file to XML file for simulation tool;
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Fig. 6 XML Data Update Algorithm

With the example algorithm shown in Fig. 6, the system was able to calculate correctly the coordinates for each cell and update related positions. In addition, other parameters within XML file can also be modified and updated according to the new requirements so that the simulation model within virtual engineering environment (i.e. vueOne) can be updated and validated based on the new design concept.

V. CONCLUSION AND FUTURE WORK

This paper proposes a novel ontology based semantic-predictive model to improve reconfiguration of automation system simulation model. An ANNE Gazetteer with semantic engine was built to transfer XML data to a computer readable data (semantic data). Using semantic data and rule-based prediction algorithms, the developed system is able to predict changes in the system design on the basis of change in the product design and requirements. Furthermore, the integration GATE and Protégé software enabled semantic-predictive model to automatically match vueOne data with PPRR ontologies using semantic technology.

The semantic-predictive model provides an opportunity to create a knowledge system to enable reconfiguration of automation systems and enable evaluation of existing automation systems using knowledge based approach. The development of such PPRR ontologies and semantic model rapidly improve design time and reduce the need for specialised skills to reconfigure and analyse manufacturing systems.

In the future, the approach will be extended to include selection of appropriate manufacturing resource components and optimising their configuration to match product suitability and production requirements. Also, PPRR ontologies will be embedded into vueOne system to build a user interface for improving system performance and semantic model will be created in an independent semantic engine with a flexible, scalable gazetteer library to enhance software portability.

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