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Smart Virtual Product Development (SVPD) System to Support Product Inspection Planning in Industry 4.0

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Abstract

This paper presents the idea of supporting product inspection planning process during the early stages of product life cycle for the experts working on product development. Aim of this research is to assist a collaborative product development process by using Smart Virtual Product Development (SVPD) system, which is based on Set of Experience Knowledge Structure (SOEKS) and Decisional DNA (DDNA). The proposed system is developed to support three key aspects of industrial product development i.e. design, manufacturing, and product inspection. Therefore, it comprises of three main modules; design knowledge management (DKM), manufacturing capability and process planning (MCAPP), and product inspection planning (PIP). It collects, stores, and uses experiential knowledge from formal decisional events in the form of set of experience (SOE). This research enlightens the working mechanism of the PIP module, and shows how experiential knowledge related to product inspection can be used during the early stages of product development process. This experiential knowledge is extracted and stored from similar products having some common features and functions. First, the basic description and principles of the approach are introduced, then the prototype version of the system is developed and tested for product inspection planning (PIP) module for the case study, which verifies the feasibility of the proposed approach. The presented system successfully supports smart manufacturing and can play a vital role in Industry 4.0.

Keywords: Smart Virtual Product Development (SVPD) system, , Product Inspection Planning (PIP), Cyber-Physical Production Systems (CPPS), Set of Experience Knowledge Structure (SOEKS) and Decisional DNA

1. Introduction

Design and manufacturing of new products depends upon some vital factors i.e. required features of the product, available materials, manufacturing processes, assembly, and measurements of parts [1]. Whereas, emergence of smart manufacturing has changed the variety and complexity of product lifecycle applications. It has created challenges for

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manufacturing industries to capture knowledge in digital form during product design, production process planning, and inspection planning. Companies are in race to gather, analyse and utilise the data and knowledge involved in product life cycle impact assessment, design improvement, and quality assurance. There are some technical barriers that barricade industries from utilizing knowledge related to product design, manufacturing, and inspection during early stages of product development. The main obstacle is a lack of a well-accepted mechanism that enables users to integrate data and knowledge [2].

Product inspection planning is an integral part of product design and its manufacturing. It determines what characteristics of a product are to be inspected, and where and when [3]. In order to guarantee the quality of product features and the processes used to manufacture the product, manufactured products must be inspected[4]. Advanced manufacturing is distinguished by high variety of customised products, tight tolerances, and quality of the products. Meanwhile, inspection of parts and assembled products has also evolved as an important segment of integrated manufacturing. This has forced the manufacturers not to rely on one-dimensional approach, where they accept or reject the product at the end. To achieve the high quality of products, companies have moved to multi-dimensional product inspection planning technique. In multi-dimensional product inspection planning technique, parts or products need to be inspected during prototyping as well as manufacturing [3].

Measurement resources have become more capable, accurate, and complex during the third industrial revolution. This has forced the manufacturing industries to automate the measurement resources by using the deep knowledge on the selection of measurement resources i.e. use of updated inspection standards and advanced metrology equipment [5]. The concept of measurement resources in this paper comprises of dimensional measuring instruments and equipment, which are used to perform product inspection and measurements. Dimensional measuring equipment is any type of hardware used in a measurement process, for example, coordinate measuring machines (CMM), vision inspection machines (VIM), fixtures, gauges, probes, probe extensions, styli, and probe tips. Measurement devices include instruments which have all the components required for measuring the parts, e.g., callipers, micrometres, dial indicators, scanners, laser trackers, and theodolites. Various gauges include block gauges, height gauges, go/no-go gauges, depth gauges, and bore gauges. The selection of measuring equipment or instrument is based on the characteristics, tolerances, and datums of the part to be measured. Unfortunately, a very few techniques for selection of dimensional metrology equipment are available [6].

Now, the world is moving towards Industry 4.0, which is transforming conventional manufacturing to smart manufacturing. Smart manufacturing opens the manufacturing loop by converting the digital parts (drawings and models) into physical parts. Whereas, product inspection closes this loop by turning physical parts into useful information and data (product inspection /measurement reports) [7]. These ongoing technological advances have a significant influence on product design and its manufacturing. Their implementation in the selection of manufacturing equipment requires cyber-physical production systems (CPPS), which promises significant increase in the flexibility and efficiency during manufacturing. In order to ensure the high quality of the designed and manufactured products, new ways of inspection are required to realize a cyber-physical inspection [8]. Product inspection planning is a key process and it plays a vital role in making an inspection effective or useless. A well-planned inspection during early stages of product development can provide the required data and knowledge to avoid wastage of time and money [7]. In order to achieve this goal, a smart virtual product development (SVPD) system was proposed in [9], which uses a collective, team-like knowledge created from relevant past experiences.

This paper is organized as follows: section 2 introduces basic concepts e.g. set of experience knowledge structure (SOEKS), smart manufacturing and cyber-physical production systems (CPPS), importance of product inspection planning in smart manufacturing, Section 3 introduces the proposed smart virtual product development (SVPD) system and explains its architecture. Implementation of product inspection planning (PIP) module, results and discussion are presented in Section 4, while the conclusions and future work are presented in section 5.

2. Background

2.1 Set of Experience Knowledge Structure (SOEKS) and Decisional DNA (DDNA)

Set of experience knowledge structure (SOEKS) has the ability to store and share the formal decision events in an explicit manner [10]. It is a smart knowledge-based decision support tool, which stores and maintains the experiential

knowledge. This experiential knowledge is used for future decision-making enhancement whenever a new query is generated or presented. A set of experience (SOE, a shortened form of SOEKS) has four basic components: variables (V), functions (F), constraints (C), and rules (R).
Variables define SOE's functions, while functions create relationships between variables and are used to develop multi-objective goals. Constraints are special functions which are applied by SOE to get feasible solutions and to control system's performance with respect to defined goals and limits. Rules, on the other hand, are the conditional relationships among the variables and are defined in terms of IF-THEN- ELSE logical statements. Therefore, a formal decision event is represented by a unique set of variables, functions, constraints, and rules within the SOE. Groups of SOEs create chromosomes, which represent the specific area/domain within the given decision-making area, and they store decisional strategies for a given domain. Accurately structured and grouped sets of decisional chromosomes are collectively known as DDNA[10].
Set of experience and DDNA have been successfully applied in various fields such as industrial maintenance, semantic enhancement of virtual engineering applications, state-of-the-art digital control system of the geothermal and renewable energy, storing information and making periodic decisions in banking activities and supervision, e-decisional community, virtual organization, interactive TV, and product innovation [11].

2.2 Smart Manufacturing and Cyber-Physical Production Systems (CPPS)

Smart manufacturing brings up the concept of integrating traditional manufacturing skills with emerging technologies to boost the manufacturing systems' efficiency, agility and sustainability. It uses the concept of cyber physical systems through the collaboration of co-elements to monitor and control the specific physical entities in the manufacturing environment [12]. It is an emerging form of production which integrates manufacturing assets of today and tomorrow with sensors, computing systems, communication technology, control, simulation, data intensive modelling and predictive engineering.
Cyber-physical systems (CPPs) together with the internet of things, cloud computing, artificial intelligence, and data science are the key components of smart manufacturing. They can be described as the transformative technologies for managing interconnected systems between its physical assets and computational capabilities with the possibility of human machine interaction [13]. CPSs have a significant impact on product creation in general and have many applications specifically in product manufacturing and forming the term of cyber-physical production systems (CPPSs).
The expected key advantage towards the employment of CPPSs is a significant increase in flexibility and efficiency concerning value chain and complex manufacturing networks. The collaborative and autonomous way of organizing and managing production processes through CPPSs opens potential applications for mass customization and new business models. But, it also raises significant challenges and implications on existing systems, organizational structures as well as established tools and methods in all areas of product creation [8].

2.3 Importance of product inspection planning in smart manufacturing

Product is something sold by an enterprise to its customers in the form of a good, service, place, organization or an idea. In this research, products are objects which are manufactured in industry for the end users. Our research is based on developing products from evolving range of products. We use an approach to develop a new product from existing product families and part hierarchies. The composition of the new product derived from product families can be formulated in terms of equations as follows [14].

$$[Product\ Family] \Leftarrow [Prod]_1 + [Prod]_2 + [Prod]_3 + .. + [Prod]_n \qquad (1)$$

A product can be further described as being made up of the structured assembly of part objects and can be expressed as [15]:

$$[Product] \Leftarrow [Part]_1 + [Part]_2 + [Part]_3 + .. + [Part]_n \qquad (2)$$

Equation (2) illustrates the idea that a product is made up of a structured assembly of n-number of different parts. The next step is to define part objects. Part object [Part] is considered to comprise of a set of six basic part properties as shown in the expression below:

$$[Part] \Leftarrow \{M \wedge \mathrm{MP} \wedge F \wedge D \wedge T \wedge SF \wedge Q\} \qquad (3)$$

As illustrated by equation (3), the set of properties associated with each [Part] include set of materials (M), manufacturing processes (MP), form features (F), Dimensions (D), Tolerances (T), Surface Finish (SF), and Quantity (Q). These properties of parts or products can be achieved by using CPPS in smart manufacturing. They are group of manufacturing resources (MRs); which include machinery, equipment, and workstations. These resources are bound together by a common material and information flow that represent the material handling systems (MHs) [14].

$$[CPPS] \Leftarrow \{M\mathrm{Rs} \wedge \mathrm{MHs}\} \qquad (4)$$

Whereas, manufacturing resources for CPPS include the networking interface (NI), the cognitive capability (CC), available sensor data (SD), and all properties associated with manufactured parts as shown in equation (3). Therefore, manufacturing resources can be expressed as[14]:

$$[MRs] \Leftarrow \left\{ \begin{array}{c} NI \\ CG \\ SD \\ \mathrm{M} \\ MP \\ Dmin - Dmax \\ Tolmin - Tolmax \\ SFmin - SFmax \\ Qmin - Qmax \end{array} \right\} \qquad (5)$$

In order to achieve the close-fitting dimensions, tolerances, and surface finishes in CPPS environment, it is very important to have a proper tool to define the product inspection planning during early stages of product development. Similarly, increased product diversity and sophistication has also resulted in the need for more automated inspection planning and improved decision making. Decisions taken during product inspection planning have a direct impact on the cost and quality of the final product. Various sequences and methods chosen during product inspection planning can be highly subjected to errors and conflicts due to a large number of configurations or improper choice of datums and references [3]. Almost, all the fields of engineering sciences involved in manufacturing of products are closely associated to each other in terms of product inspection. Therefore, the manufacturing industries require knowledge of various inspection and testing methods to comply with the products' technical requirements and acceptance criteria [16].

3. Introduction to Smart Virtual Product Development (SVPD) System

Smart Virtual Product Development (SVPD) system is a decision support tool to support industrial product development process. This approach uses a smart knowledge management technique called Set of Experience Knowledge Structure (SOEKS or SOE in short) and Decisional DNA [17]. It captures, stores, and shares the experiential knowledge in the form of set of experiences (SOEs) during important phases of industrial product development i.e. product design, manufacturing, and product inspection planning (quality aspects).Whenever a similar query is presented during the problem solving process, this stored knowledge is recalled to overcome the problem. It provides a list of proposed optimal solutions according to the priorities set by the user. By the passage of time, the system achieves more expertise in specific domains as it stores relevant knowledge and experiences related to formal decision events. The developed approach helps in overcoming the need to manually capture the knowledge during various stages of smart manufacturing e.g.: product design, manufacturing, and inspection planning [2]. It will be helpful in transforming recent successful lean product development approaches to smart manufacturing in Industry 4.0 scenario.

3.1 Architecture of Smart Virtual Product Development System

Smart Virtual Product Development (SVPD) system consists of three main modules, namely: design knowledge management (DKM), manufacturing capability analysis and process planning (MCAPP), and product inspection planning (PIP). These modules interact with the decisional DNA of the system which holds all the relevant knowledge of the similar products. This knowledge repository is filled with the past formal decisional events involved in manufacturing of these similar products within existing facility. The proposed system stores the knowledge in the form of SOEs. The architecture of the SVPD system is shown in Fig. 1.

Design knowledge management (DKM):
Design knowledge management module helps in providing the knowledge related to design engineering to the experts during early stages of product development. This module consists of two sub-modules i.e. material selection process and product geometric features generation. Material selection is one of the main functions of effective engineering design, since it defines the reliability of the design in both industrial and economical aspects. The selection of the best materials for a specific component is an activity usually carried out by design engineers, where the chosen materials should satisfy all the requirements such as strength, stiffness, cost and aesthetics [18]. Knowledge and experience are one of the main factors to influence the choice of materials and manufacturing processes.

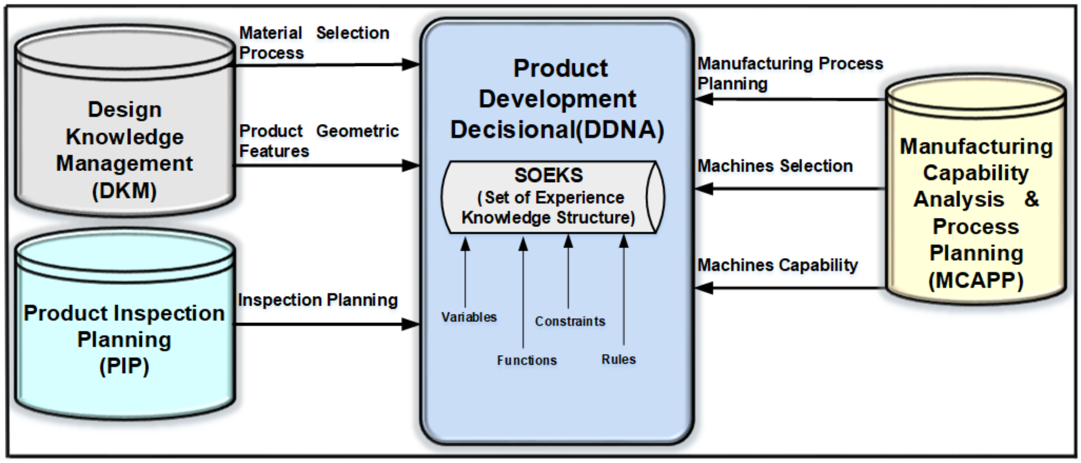

Fig. 1. Architecture of Smart Virtual Product Development (SVPD) system.

Product design is one of the most important phases in product development. It affects right from material selection, manufacturing and assembly processes to the product distribution, use, reuse, recycle and disposal. Although the design process constitutes only 5-7 percent cost of the whole product development, however, it can determine around 75 percent of the entire product life cycle cost. Product design is a complex process which requires knowledge of various fields. Generally, a designer working on engineering design requires three types of knowledge; knowledge to generate ideas, knowledge to evaluate ideas and to make decisions, and knowledge to structure the design process. Experience and natural ability are key factors in idea generation, whereas idea evaluation is achieved partially through formal training and experience. Generative and evaluative knowledge are the forms of domain-specific knowledge. Knowledge about the design process and decision making is largely independent of domain-specific knowledge [19]. Effectiveness of the design process is measured in terms of product cost, quality, and time to market. Customers and management always want the product to be cheaper (lower cost), better quality, and faster (less time to market). Most of the design tasks are dependent upon a huge amount of expert knowledge and supporting information. If a proper decision support is provided to the designers, it can free them from the drudgery involved in searching and locating appropriate knowledge [19]. In our previous research, the working mechanism of material selection process was presented [9, 20], where the knowledge and past experiences were effectively utilized for the material selection of a threading tap.

Manufacturing capability analysis and process planning (MCAPP):
Manufacturing capability analysis and process planning module assists in providing the manufacturing knowledge to the experts during early stages of product development. It comprises of further three sub-modules i.e. manufacturing process planning, machines' selection, and machines' capability.
Manufacturing process planning deals with the manufacturing processes required to manufacture the product in the existing facility i.e. machining, sheet metal work, casting, forging, press work etc. Manufacturing process plans are designed to ensure consistency and use of best available machinery in the existing facility. The first step in defining the manufacturing process plan is to recognize a set of geometric features and their interrelationships from the part design. Set of machining functions are selected based on the product geometric features, which can be treated as a general machining process without detailed machining methods [21]. The sub-modules: machines' selection, and, machines' capability, involve the selection of suitable machine tools to perform the required manufacturing operations. The working mechanism of manufacturing process planning was presented in [22, 23] our previous research, where the effective use of knowledge and past experiences for generating the manufacturing process plan for a threading tap was proposed.

Product inspection planning (PIP):
Product inspection planning module includes the selection of suitable measuring instruments and equipment required to inspect the critical geometric features of product during its prototyping and manufacturing processes. Once all of these modules are successful, proposed system provides the validation that a product can be easily manufactured in the existing facility. The purpose of this research is to explain the working algorithm of PIP- module.

4. Implementation of PIP- Module

Product inspection planning (PIP) module is designed to support product inspection planning process for the manufactured products. It provides inspection plans in terms of product's metrology and testing (mechanical, electrical, or functional). Metrology is the science of measurement and its corresponding accuracy, precision, and uncertainty. It determines length, angle, and any other advance geometric dimensioning and tolerancing (GD&T) features. These features could be; circularity, true position, perpendicularity, flatness, symmetry, straightness, concentricity, cylindricity, and parallelism among others. Therefore, dimensional measurement and inspection are synonymous with dimension metrology. Dimension metrology is essential for manufacturing the parts correctly and is based on complex 3D-geometric entries and their relationships. These geometries are associated with large diverse knowledge based that has many interconnections with entities such as the measurement process, devices, standards, traceability, and statics [24]. Dimensional metrology process can be divided into four major interacting elements: product definition, measurement process planning, measurement process execution, analysis and reporting of the data [25]. Therefore, in order to generate product inspection process plan information it is very important to know: what features need to be measured, purpose of measurement, and available measurement resources to be used (instruments and devices) [24].

4.1 Working algorithm for PIP module

Design and development of machine use threading tap continues to be our case study to generate a product inspection plan, as it was also used for DKM and MCAPP modules in our previous research [9, 22]. Similarly, the parser for reading product inspection planning is written in JAVA, as the parser for interpreting DKM and MCAPP modules were also written in the same format. Comprehensive information about product inspection planning for manufactured threading taps of the same family is stored in the form of SOEKs in a Comma Separated Values (CSV) file. Whereas, SOEKs store this data in the form of sets of variables, functions, constraints, and rules. The CSV file contains data in standard format so that the parser collects the information as required. For illustrative purpose CSV file for product inspection planning for various geometric features of threading taps is shown in Table 1.

Table 1: CSV File format for Product Inspection Planning (PIP)

Variables

Product	Material	Mach_Operation	Feature	Instrument	Instrument_ID	Inspection_Station
Threading Tap	T11301	Laser Cutting	Length	Vernier	T123470	On-Machine
Threading Tap	T11302	CNC Turning	Diameters	Micrometer	T123471	On-Machine
Threading Tap	T12001	CNC Milling	Angles	CMM	T123472	Metrology lab
Threading Tap	T12002	Heat Treatment	Hardness	Hardness Tester	T123473	Mechanical Lab
Threading Tap	T12003	Thread Grinding	Minor Diameter	Vision inspection	T123474	Metrology Lab
Threading Tap	T11301	Laser Cutting	Length	Vernier	T123470	On-Machine
Threading Tap	T11302	CNC Turning	Diameters	Micrometer	T123471	On-Machine
Threading Tap	T12001	CNC Milling	Angles	CMM	T123472	Metrology lab
Threading Tap	T12002	Heat Treatment	Hardness	Hardness Tester	T123473	Mechanical Lab
Threading Tap	T12003	Thread Grinding	Pitch of thread	Vision inspection	T123474	Metrology Lab

The working procedure of PIP-module is shown in Fig.2 and explained below as:

- First the parser looks for the term 'Variables' and goes to the next line. The first line after the term 'Variables' contains the name of Variables. It stores values written in each cell of the first line as the 'Name' of the Variables. Each line after this contains the values of corresponding Variables. The parser assigns the values to the respective Variables. This group of Variables is stored in the system as one 'Set of Variables'.
- Similarly the parser reads the second set of values from the CSV file and assigns them to the respective Variables which are stored as the second 'Set of Variables'.
- The same process continues until the parser finds the term 'Functions', 'Constraints', or 'Rules'. In the same way, the parser reads 'Set of Functions', 'Set of Constraints', and 'Set of Rules' from the CSV file. One 'Set of variables' plus 'Set of Functions', 'Set of Constraints', and 'Set of Rules' are combined together to form SOEKS.
    - *SOEKS = Variable set + Function set + Constraint set + Rule set*
- User provides Input Query in terms of Variables, functions, and constraints. This new Query is converted into new SOE i.e. Query SOE
- System finds the similarity of Query SOE with SOEKS stored in the CSV file. Similarity is calculated on the basis of Euclidian distance with its value ranging from 0 to 1 (0 being the closest).
- System provides output in the form of top five proposed solutions with minimum similarity.
- User selects the final solution and query SOEKS is updated and saved as a SOEKS in SVPD-DDNA.

4.2 Results and Discussion

Case study for product inspection planning was carried out on a Dell laptop with windows 10 Enterprise 64-bit operating system having Intel ® Core ™ I5-7300u CPU @ 2.60 and 8 GB of RAM. Parser for PIP-module reads the data from a CSV file having information about 10 different types of threading types according to material classification, type of manufacturing operation, and geometric features to be measured etc. This CSV file stores the relevant data in the form of 20 variables, 2 functions, and 3 constraints. The parsing process was executed, producing an average parsing time of 0.084 seconds, as depicted in Fig.3. This is considered a very good time, taking into account that those SOE are quite complex due to the substantial number of variables, functions, and constraints. Similarly parsing time for different SOE elements was; time to read variables 0.032 seconds, time to read functions 0.037 seconds , and time to read constraints was 0.014 seconds respectively.

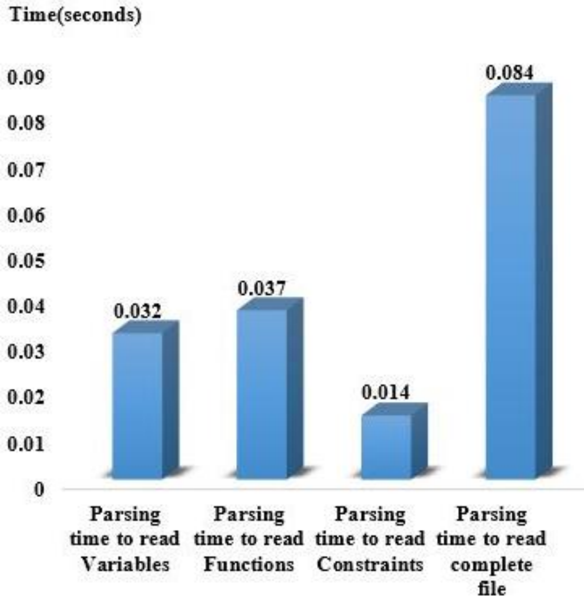

Fig. 3. Parsing time vs SOE elements for product inspection planning module.

5. Conclusion and Future Work

This research revealed a system to support product inspection planning of industrial manufactured products by using the experiential knowledge. The system is composed of three modules, namely design knowledge management module (DKM), manufacturing capability analysis and process planning (MCAPP), and product inspection planning (PIP). The working algorithm of PIP module has been explained by developing it in JAVA. The analysis of basic concepts and implementation method proves that SVPD is an expert system, which can facilitate Cyber-Physical Systems (CPS) and can play a vital role towards the establishment of Industry 4.0.

Proposed system is capable of enhancing the product inspection planning by using the past experiential knowledge of the similar products. Provision of product inspection planning knowledge to experts during early stages of product development is illustrated with an example of a case study, which also helps to understand the architecture and working of the proposed system. The proposed system is dynamic in nature as it updates itself every time a new decision is made. It will benefit the entrepreneurs and manufacturing organizations involved in new product development process by reducing the extent of dependability on experts. The future work includes the refinement of the algorithm for PIP module in more details.

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