IoT and Cloud Computing in Automation of Assembly Modeling Systems

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***Abstract*—After the technologies of integrated circuits, personal computers, and the Internet, Internet of Things (IoT) is the latest information technology (IT) that is radically changing business paradigms. However, IoT's influence in the manufacturing sector has yet been fully explored. On the other hand, existing computer-aided software tools are experiencing a bottleneck in dealing with complexity, dynamics, and uncertainties in their applications of modern enterprises. It is argued that the adoption of IoT and cloud computing in enterprise systems (ESs) would overcome the bottleneck. In this paper, the challenges in generating assembly plans of complex products are discussed. IoT and cloud computing are proposed to help a conventional assembly modeling system evolve into an advanced system, which is capable to deal with complexity and changes automatically. To achieve this goal, an assembly modeling system is automated, and the proposed system includes the following innovations: 1) the modularized architecture to make the system robust, reliable, flexible, and expandable; 2) the integrated object-oriented templates to facilitate interfaces and reuses of system components; and 3) the automated algorithms to retrieve relational assembly matrices for assembly planning. Assembly modeling for aircraft engines is used as examples to illustrate the system effectiveness.**

***Index Terms*—Assembly modeling, cloud computing, computer-aid manufacturing, computer-aided process planning, Internet of Things (IoT), product templates.**

I. Introduction

BUSINESS markets have been globalized, and inter-enterprise and intra-enterprise interactions become strongly coupled. Within an enterprise, the departments (e.g., *design*, *manufacturing*, *assembly*, and *marketing*) work concurrently to optimize products and manufacturing processes at the system level. Outside an enterprise, inter-enterprise collaborations (e.g., *global manufacturing*, *virtual manufacturing*, and *enterprise alliances*) aggregate all possible resources to make complex products. Meanwhile, companies are able to reconfigure themselves to catch new market opportunities. Conventional enterprises with static system architecture, such as *computer-integrated-manufacturing*, are no longer able to cope with high-level complexity and turbulences in a dynamic environment. Many manufacturing paradigms, such as *agile manufacturing* and *sustainable manufacturing*, have been proposed to meet these challenges [4]–[6]. However, the implementation of a new paradigm relies on the infrastructure of information technology (IT). IT technologies and innovations, including newly developed Internet of things (IoT), have been stimulating manufacturing technologies.

According to the Moore's law, the processing speed and memory capacity of computing hardware double every 18 months [8]. After the breakthroughs of large-scale integrated circuits, personal computers, and the Internet, many speculators believe that the next IT revolution is IoT. An interacting network with billions even trillions of the tracked objects becomes feasible. Direct interactions can be performed among objects and humans. Successful applications of IoT have been demonstrated in retail business, logistics, military, environment surveillance, and healthcare [36]. In those applications, real-time data can be collected by numerous sensors and the data can be shared by the network to support decision-making. However, IoT's potential in many areas, including design and operation of manufacturing systems, has yet been explored systematically.

In this paper, IoT is proposed to be applied in automated assembly planning system, since IoT can be a vital solution to address system complexity and uncertainties. The rest of the paper is organized as follows. Section II provides a literature survey on automated assembly modeling to identify the limitations and challenges of existing techniques. The rationales that IoT can be a potential solution to overcome these limitations have been explained. Some enabling technologies are introduced to evolve conventional assembly planning system into an advanced IoT-based information system. In Section III, the object-oriented model template is proposed to address the requirements of decentralization, modularity, and expandability. In Section IV, new data mining algorithms are considered for cloud computing. Automated algorithms are developed to retrieve relational matrices for assembly modeling. In Section V, assembly modeling for aircraft engines is used as a case study to illustrate the application of object-oriented product template and algorithms. In Section VI, the presented work is summarized and the conclusion is provided.

II. Literature Review

From the perspective of interaction and communication, the world is becoming flatter and smaller and the manufacturing

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business environments are globalized. In other words, the production involves many resources, which are interacted with each other and should be taken into consideration simultaneously in decision-making of business activities. This forms new challenges to an enterprise system (ES) in terms of the requirements on dealing with decentralization, modularity, and expandability. The recent progress on the development of ESs has been given by Xu [53] and He and Xu [22]. The implementation of an ES depends on the IT infrastructure. In the following, ESs for assembly modeling and their correlations with IoT are discussed.

A. ES for Automated Assembly Modeling

Modern products tend to be smarter, more versatile, and sophisticated. Product structures become even complex, which poses critical challenges in assembly processes. System performance, such as profit, lead-time, quality, and cost, depends greatly on the effectiveness of assembly modeling [11], [17], [18]. *Digital assembly* is a type of ESs for assembly planning based on solid models and structures of products. The level of difficulty of assembly modeling depends on the complexity of a product, as well as the availability of data for assembly planning. The adoption of IoT in a modeling system will have a significant impact on these two aspects.

1) Complexity: To quantify the complexity, a system can be viewed as a constitution of inputs, outputs, and the relational models from inputs and outputs. System complexity relates to the number of system components, which may be varied significantly from one system to another [9], [44]. Modern products include more and more components and their production processes involve uncertainties. Both factors increase system complexity, as well as the complexity of computer-aided design (CAD) systems. The rising complexities involved in decision support systems have been explored broadly in the literatures. For example, Li *et al.* [30] investigated the qualitative and quantitative data and reasoning involved in design of complex products; they developed an approach to represent and utilize vague and qualitative data to manage the complexity of product design. Basanta-Val and Garcia-Valls [3] developed a Java-based architecture to deal with the heterogeneity and distribution of information systems in industrial applications. To monitor real-time changes in industrial control systems, Vollmer *et al.* [48] investigated intelligent cyber sensors for the purpose of the enhanced security and the controllability of system complexity.

2) Data Availability: A manufacturing company used to have its clear boundary with its residential environment to define its inside business activities. The company was organized as a hierarchical architecture, and all data and information were integrated and could be accessed from a centralized database by decision makers. The corresponding system paradigm was computer-integrated manufacturing (CIM) [4], [5]. CIM could optimize the utilization of system resources to achieve a high productivity. However, it involved a heavy cost and lacked of adaptability to accommodate quick changes [6], [16]. To improve system adaptability, a manufacturing system becomes dynamic and its boundaries with the environment become vague. Close interactions are needed in both of inter-enterprise and intra-enterprise collaborations. Correspondingly, the data required by decision-making at the high level is decentralized and must be accessed readily by distributed participators [7].

Although no assembly modeling system can meet the aforementioned requirements appropriately, many researchers have contributed to the fundamentals of digital assembly. Since 1980s, scientists have developed various assembly modeling methods, such as *map-based relation models*, *hierarchical tree models*, and *object orientated models*. Note that in assembly modeling, how to define assembly relations among parts is critical. As far as assembly relations are concerned, the examples of the relational models are *liaison diagram models* [18], AND/OR *Representations* [38], and *polychromatic models* [20], [59]. Among these models, matrices are widely used since they are efficient to represent the relations and easy to be programmed. Dini and Santochi [13] first used the matrices to represent assembly models of products; they proposed the *interference matrix*, *contact matrix*, and *connection matrix* to describe product structures, sub-assembly components, and assembly sequences. Huang and Huang [23] improved Dini and Santochi's model with a concept of discomposed binary matrix, which was represented in a tree diagram. However, the limitation of their models [13], [23] is that the interference matrix is inapplicable when parts have inclined surfaces for assembling. To accommodate this case, the contact matrix and connection matrix have to be determined manually. Yu *et al.* [56] extracted the relation matrix from the object relation chart for the connection information of parts; which required inputting the object relation chart manually. Wang and Liu [58] utilized the neighboring matrix and interference matrix that was similar to the contact matrices. To simplify the modeling process, Shu *et al.* [43] constructed the connection matrix and interference matrix, which only considered functional parts.

B. IoT and Its Applications

The advance of an ES relies greatly on IT infrastructure. IoT is becoming a mainstream infrastructure [39]. IoT can help companies to catch emerging opportunities and improve competitive advantage [33]. A number of researchers gave their comprehensive surveys on the state of the art of IoT. For example, Kranenburg *et al.* [28] introduced a brief history of IoT; Bandyopadhyay and Sen [8] overviewed key technological drivers, potential applications, and challenges of IoT; Bui [9] and Atzori *et al.* [2] discussed the progress of the development in enabling technologies. He and Xu discussed the requirements of information integration for distributed enterprises [22]. Li surveyed existing information technologies to fight counterfeit products in the globalized market [29]; while Xu focused on information architecture for quality management in supply chain [53]. The application of IoT was also extended to water resource management under critical weather conditions by Fang *et al.* [19]. The work by Li *et al.* discussed the technologies to improve the efficiency of data acquisitions and transmission in an IoT-based application [32]. The IoT has not only been studied by the developed countries such as the United States, Japan, and European countries, but also by the rapidly developing countries. Taking an example of China, 43% of large organizations started to test and investigate the private clouds and infrastructures of IoT and this percentage was predicted to be 88% in two years from 2011 [41].

Cloud computing is a critical technology to support decision-making systems of IoT-based applications [42], [31], [33], [49]. The issues involved in the application integrations of hybrid cloud computing environment were discussed by Li *et al.* [31]. Architectures to support the operations of distributed enterprises were investigated by Tan *et al.* [45] and Wang *et al.* [50]. To establish better client–server relationship, Ren *et al.* [42] developed a simulation platform as a computation tool for design of complex products. Tao *et al.* [47] proposed a parallel method to deal with the service selections in cloud manufacturing, and Cheng *et al.* [10] scheduled services based on energy saving in cloud manufacturing.

Despite the rapid development of IoT, many challenges were raised to adopt the IoT in different applications [37]. To achieve ambient intelligence, major technological innovations will need to take place. These include governance, standardization [25], [26], [27], interoperability [24], [40], [51], and efficient and secure communication protocols [16]. Today's business models are mostly based on static information architectures; these models face challenges when the collected data are dynamic and hard to be predicted. A successful IoT application must be capable of supporting decision-making on complex objects [12].

C. IoT for Assembly Modeling

The challenges of ES for manufacturing enterprises are to achieve system capability in dealing with the complexity and decentralization of decision-making activities. The enablers of assembly modeling must be modularized, decentralized, and automated. IoT will provide the solution to these challenges. On one hand, the private cloud or hybrid cloud can be established so that any data can be accessed by users, no matter how and where the suppliers are geographically distributed. Regarding the dynamics of data, IoT links all of the objects together, they are monitored and real-time data can be collected. Uncertainties can be identified to support optimized decision-makings. On the other hand, IoT uses the service-oriented architecture [21], [40], [41], [47], [50]; accessible distributed tools in IoT are modularized and interoperable. They can be aggregated to fulfill some complicated decision-makings as needed. As shown in Fig. 1, IoT provide the access of the distributed data from all of the vendors related to assembly processes. The server for assembly modeling and planning in private or a hybrid cloud will be treated as an object of IoT; i.e., the assembly modeling and planning will be accomplished by *cloud computing*.

III. Object-Oriented Product Model Templates

The IoT links distributed resources. For example, the CAD models of parts for a complex product are developed at different places, and assembly modeling and planning of the product is accomplished at another place. It is desirable that the product structure is modularized, so that components in assembly are loosely coupled. The participators can modify and maintain their own part models without an unnecessary impact on the general assembly model. *An object-oriented model template* can meet

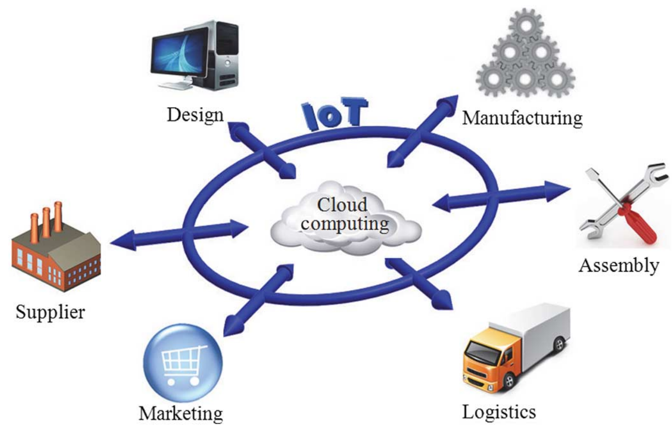

Fig. 1. IoT application for assembly modeling and planning.

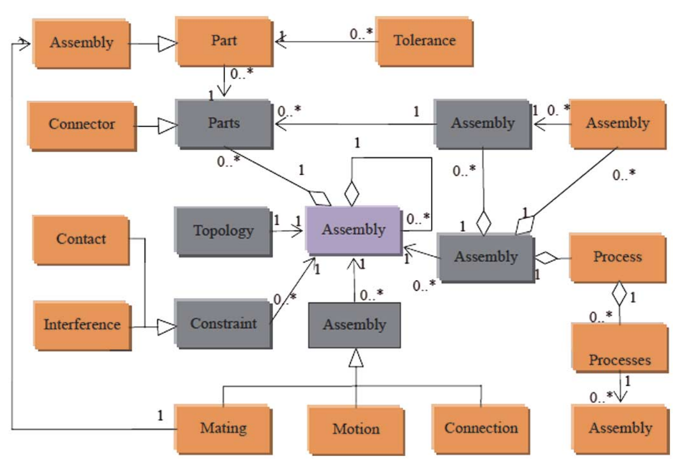

Fig. 2. Model template of product.

these requirements appropriately. An object-oriented model template is also helpful to alleviate the complexity of product development since less number of interactions will be involved. Cooper and James [15] discussed the challenges of data management in IoT; computer representation of physical objects is needed to allow modeling and simulation of physical scenarios. To develop an assembly modeling system on the IoT infrastructure, we propose a new methodology based on object-oriented templates: a model template of product family is first developed and the assembly model can be instantiated from the defined template [54], [57].

A model template represents basic elements and their relations of products for a product family. To facilitate assembly modeling, a model template should include all required information such as the classes of parts or components, assembly topologies, options of connections, and assembly plans. Fig. 2 shows an example of a model template. It consists of a hierarchical product structure; i.e., a high-level assembly consists of a set of low-level sub-assemblies. Each assembly consists of the classes of parts or sub-components, assembly relations, constraints, as well as the assembly sequence. Depending on the requirements, each class can be exploded to contain its detailed attributes. For example, the class of *constraint* is exploded so that the conditions for *contact* and *interference* can be defined.

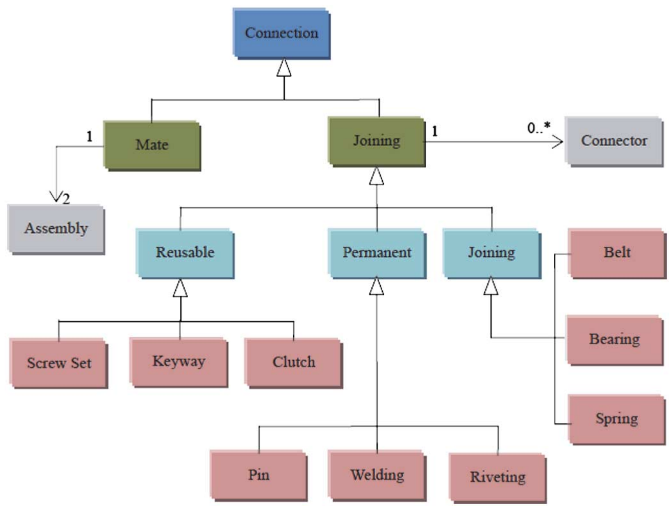

Fig. 3. Class diagram of assembly connection relations.

Topological relations can be defined separately for an assembly model template. Fig. 3 shows a classification of assembly relations based on the physical connections between two parts. For example, parts can be connected in *temperately, permanently*, or with a *joining* relation, which allows a relative motion. For a temperate connection, different parts, such as *screw set*, *keyway*, or *clutch* can be applied.

IV. Algorithms to Automate Assembly Modeling

For assembly modeling, the critical tasks are to define the assembly relations from given product CAD models automatically. In this section, the assembly relations and interference relations among parts and sub-assemblies are mainly concerned, and the algorithms to retrieve the matrices for these relations automatically are proposed.

A. Matrix $\boldsymbol{M}$ for Assembly Relations

A complex product usually consists of many parts and sub-assemblies. The most important information in a model template for the product assembly is the connection relations of parts. To retrieve it from the model template, a matrix $\boldsymbol{M}$ for assembly relations is defined as follows:

Assume a model template P of a product consists of N parts, i.e., $P = \{p_1, p_2, \ldots, p_N\}$. An integer m_{ij} $(i = 1, 2, \ldots, n;$ $j = 1, 2, \ldots, n)$ represents the connection of p_i and p_j as

$$m_{ij} = \begin{cases} 0 & \text{if } p_i \text{ and } p_i \text{ are separated} \\ 1 & \text{if } p_i \text{ is a function part, } p_j \text{ is a function part,} \\ & \quad \text{and } p_i \text{ and } p_j \text{ are contacted} \\ 2 & \text{if } p_i \text{ is a function part, } p_j \text{ is a function part,} \\ & \quad \text{and } p_i \text{ and } p_j \text{ are connected} \\ 3 & \text{if } p_i \text{ is a connection part (screw or bolts)} \\ 4 & \text{if } p_i \text{ is a connection part (nuts)} \\ 5 & \text{if } p_i \text{ is a connection part (keys)} \\ 6 \geq 6 & \text{if } p_i \text{ is a connection part (others).} \end{cases}$$

Thus, $\boldsymbol{M} = [m_{ij}]$ is an $N \times N$ matrix for the assembly relations of the product.

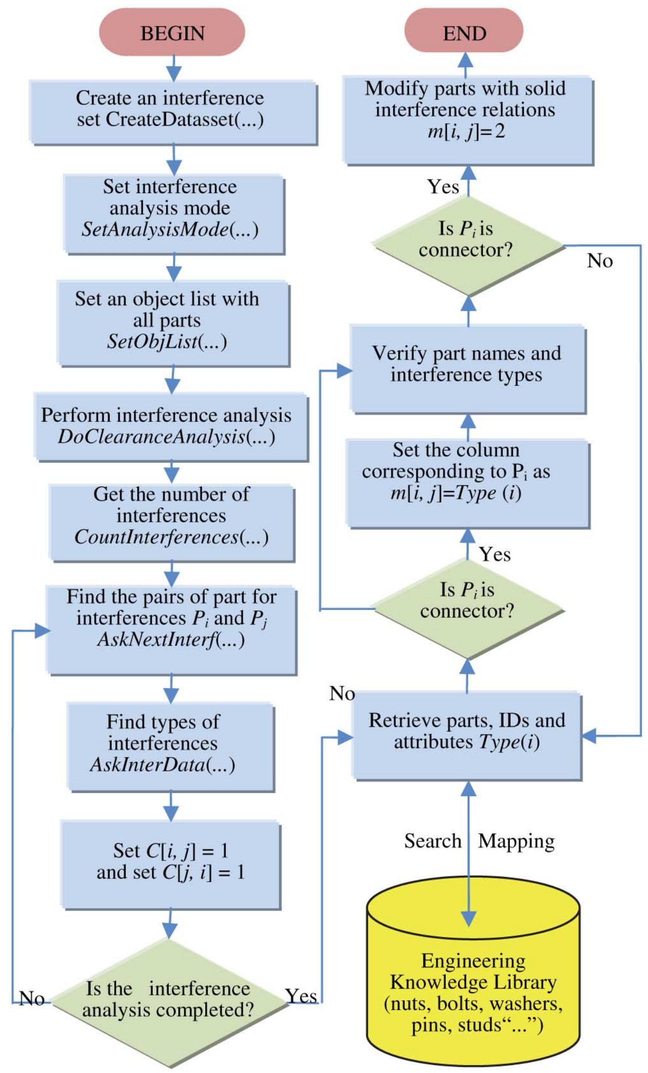

Fig. 4. Flowchart of generating the matrix of assembly relations.

B. Interference Analysis in Generating Matrix $\boldsymbol{M}$

In defining assembly relations, two parts can be "*closed*," "*touched*," or "*interfered*" with each other. A "closed" relation happens when the distance between two parts is less than the tooling size. A "touched" relation happens when two parts make a physical contact without interference. An "interfered" relation happens when a spatial volume is shared by two parts. Note that an interfered relation is not always inappropriate. For example, a screw and nut should have an interfered relation so that the fastening works adequately. However, it is critical to analyze the interference in determining an assembly plan. Fig. 4 shows the process of generating the matrix $\boldsymbol{M}$ of assembly relations with an interference analysis. Matrices $\boldsymbol{M}$'s for assembly relations are derived from the spatial positions of parts in an assembly. Once a part is placed, all of its spatial relations with other parts can be defined correspondingly. The derived matrices $\boldsymbol{M}$'s of assembly relations can be integrated into any computer assistive software for assembly planning. For example, such matrices can be utilized in sequence planning to define assembly or disassembly paths as explained in Section III-C.

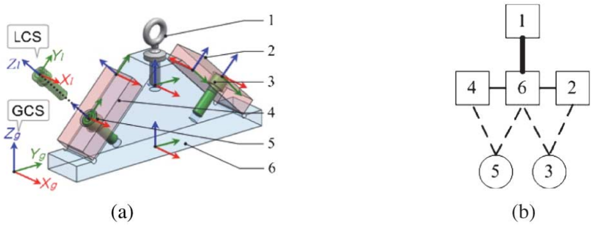

Fig. 5. Example of components with inclined assembly direction: (a) assembly and (b) contact relations.

C. Extended Matrix for Assembly Paths

An extended matrix (EM) can be defined to include the directions of assembly or disassembly. The directions should be determined to avoid any interference along a path. No algorithm has yet been reported to identify interference-free paths automatically. In defining an EM, every part is positioned with respect to its local coordinate system (LCS). LCS is usually attached on the base feature of the part. It is desirable that a direction for assembly or disassembly is coincident with an axis of LCS or global coordinate system (GCS). For example, if a thread is made on an inclined surface, the assembly direction for a screw should be in line with an axis perpendicular to the inclined surface.

Therefore, the directions of assembling or disassembling can be specified either in the GCS or in an LCS. Denote the axes of GCS and LCS as (X_G, Y_G, Z_G) and (X_L, Y_L, Z_L), respectively; available operations of assembly directions for each part include $(-X_G, -Y_G, -Z_G, +X_G, +Y_G, +Z_G)$ and $(-X_L, -Y_L, -Z_L, +X_L, +Y_L, +Z_L)$; where subscripts G and L represent GCS and LCS, respectively.

Assume that an assembly model P consist of N objects with $P = \{p_1, p_2, \ldots, p_N\}$. The label em_{ij} represents the direction of assembly or disassembly of p_i with respect to p_j, and the options of directions are $(-X_G, -Y_G, -Z_G, +X_G, +Y_G, +Z_G, -X_L, -Y_L, -Z_L, +X_L, +Y_L, +Z_L)$ as shown at the bottom of the page. Then, $\boldsymbol{EM} = [em_{ij}]_{12\times \mathrm{N}\times \mathrm{N}}$ is called an extended matrix (EM). Taking an example of the component in Fig. 5, its $\boldsymbol{EM}$'s along $+Z_G$ and $+Z_L$ are

$+Z_G$	1	2	3	4	5	6
1	0	0	0	0	0	1
2	0	0	2	0	0	0
3	0	2	0	0	0	2
4	0	0	0	0	2	0
5	0	0	0	2	0	0
6	2	2	2	2	2	0

$+Z_L$	1	2	3	4	5	6
1	0	0	0	0	0	1
2	0	0	2	0	0	0
3	0	0	0	0	0	1
4	0	0	0	0	2	0
5	0	0	0	0	0	1
6	2	2	2	2	2	0

When planning an assembly sequence, parts with a negative value mean that they have been disassembled to avoid unnecessary calculation. Planning an assembly sequence needs other matrices for other relations, which can be defined to integrate assembly relation matrices $\boldsymbol{M}$'s and $\boldsymbol{EM}$'s. For example, assembly relations used in [1] can be defined from the assembly relations in $\boldsymbol{M}$'s and the interference relations can be found in $\boldsymbol{EM}$'s. Due to the complexity of relations, the dynamic generation of $\boldsymbol{EM}$'s takes more computation than the generation of assembly matrices $\boldsymbol{M}$'s. The procedure of the automated generation of $\boldsymbol{EM}$'s is depicted in Fig. 6. p_i denotes a current part to be analyzed and p_j denotes a part having an assembly relation

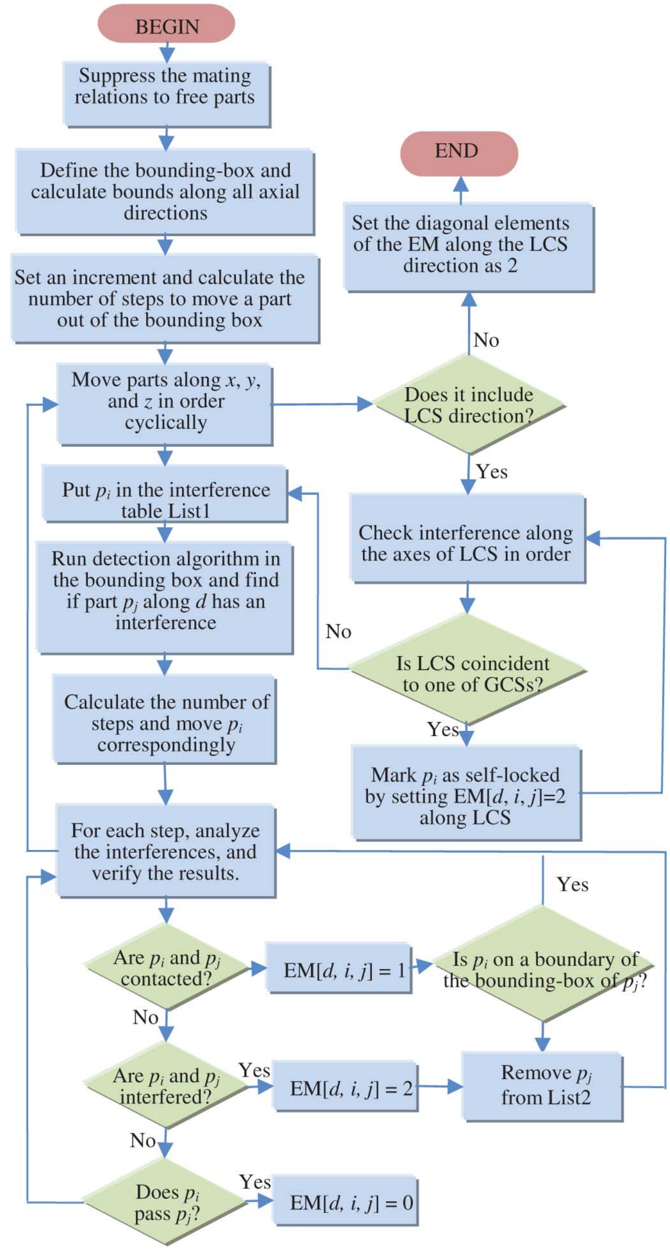

Fig. 6. Procedure of generating EMs.

$$em_{ij} = \begin{cases} 0 & \text{if } p_i \text{ does not interfere with } p_j \text{ when moving along } d \\ 1 & \text{if } p_i \text{ has a contact interference with } p_j \text{ when moving along } d \\ 2 & \text{if } p_i \text{ has solid interference with } p_j \text{ when moving along } d. \end{cases}$$

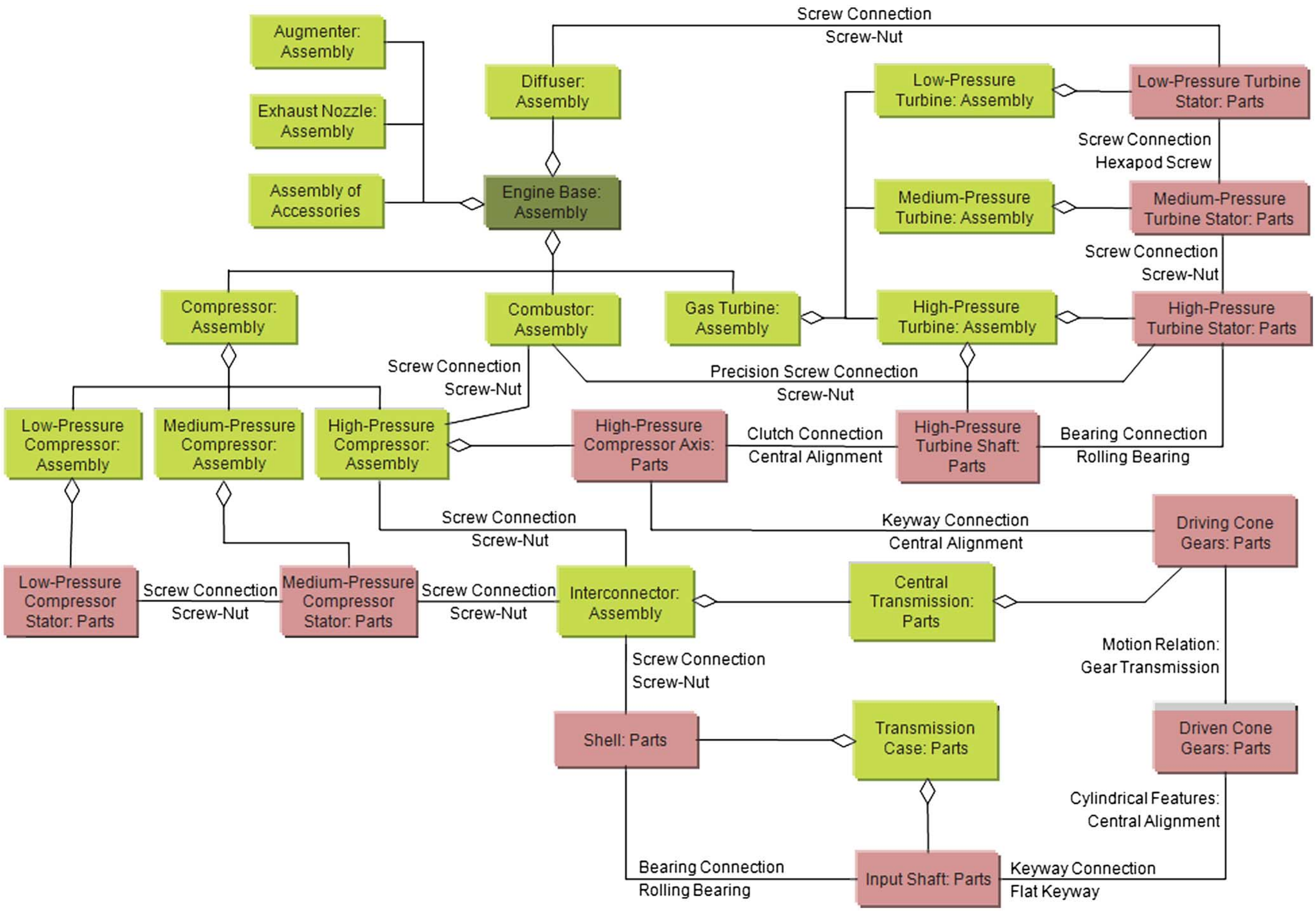

Fig. 7. Model template of gas engines.

with p_i. Due to intensive computation, it is recommended to suspend other processes when the generation of $\boldsymbol{EM}$'s is in process.

After both $\boldsymbol{M}$'s and $\boldsymbol{EM}s$ are defined, the next step is to plan assembling processes. It is not uncommon that a part has multiple ways to be assembled, numerous combinations of assemblies should be assessed in assembly modeling of a complex product. An assembly plan consists of a *scheme of processes*, *assembling paths*, and *sequence of assemblies*. In a scheme of processes, assembling resources are defined, the tolerances are given, and assembly paths are specified. An assembly path refers to a feasible route for assembling operations. A sequence of assemblies gives the order to put all parts together as a final product. It should be noted that the planning of assistive tooling, such as fixtures and gauges, has not been considered in this paper.

V. Case Study

To validate the effectiveness of the proposed method, planning of the assemblies of aircraft engines is used as a case study. Engines are complex products, since a typical aircraft engine has thousands of parts [14], [35], [60]. Until now, a standard reference model is not available to the automated assembly planning. Therefore, a model template in Fig. 7 is first developed for the assembly planning of the main bodies of gas engines. Note that the template defines basic parts and components, as well as their assembly relations in the product. At a high level, an engine is built from three main components: *compressor* section, *combustor* section, and *turbine* section. Each component can be decomposed into a new level to define the sub-catalogues of components. For example, a turbine can be classified according to its working pressure into *low*-, *medium*-, or *high-pressure* turbine. Any one of turbine includes stators and shafts. Numerous assembly relations are involved in the template. The implemented system is capable of: 1) creating assembly plans with the information from solid models, product data management, and designers' inputs; 2) simulating and visualizing assembly processes; and 3) evaluating assembling plans.

An example of the generated assembly relation matrix is shown in Fig. 8. It is a sub-assembly with 30 parts, and when the model of sub-assembly is loaded, the system first extracts the information of parts to construct an assembling tree and calculates the bounding-box to determine the movement boundary of each part when they are able to move. According to its structure, we choose "partial coordinate axis" steeping interference detection. The system calculates the insert points according to the length of each step, and drives it forward by steps. During this process, the assembly relation matrices $\boldsymbol{M}$'s and $\boldsymbol{EM}$'s are generated by using the proposed algorithms and the graphic user interfaces (GUIs) allow users to access the retrieved information. Fig. 8 has shown the examples of the graphic user information to access $\boldsymbol{M}$'s and $\boldsymbol{EM}$'s.

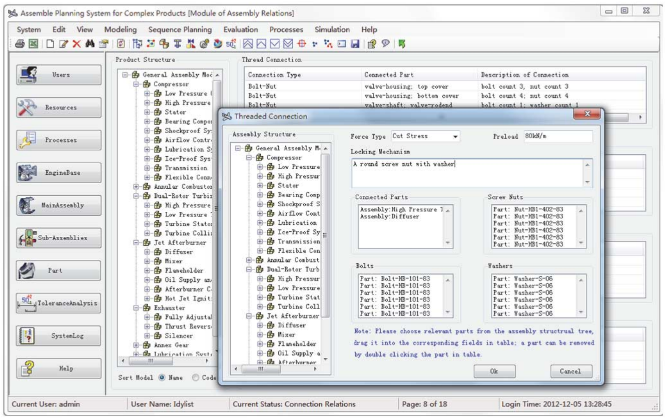

Fig. 8. GUI to retrieve $\boldsymbol{M}$'s and $\boldsymbol{EM}$'s.

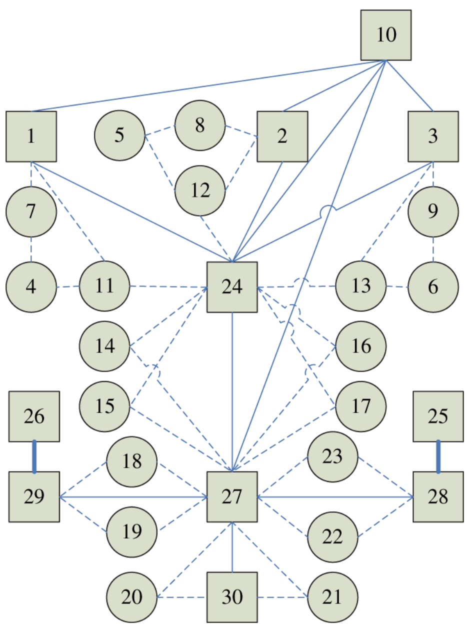

Fig. 9. Chart of contact connections.

According to $\boldsymbol{EM}$'s through inference analysis, we can further get the connection relations as shown in Fig. 9.

By tests, the output $\boldsymbol{M}$'s and $\boldsymbol{EM}$'s fit the real situation very well. It took 360 s by HP8400 graphic station to finish the steeping precision detection, whereas the bounding-box scan algorithm only took 70 s after the optimization for, the consistent direction detection and hidden mode interference detection. The CAD assembly model under other platforms (such as SolidWorks, Pro/E, etc.) can also be converted to UG platform with the parasolid file format. Once the assembly relational matrices are defined, correlated tasks such as assembling sequence planning, simulation, and generation of exploded views can be fulfilled automatically by the reported AutoAssem system [55].

VI. Summary and Conclusion

The success of ESs in manufacturing applications relies on the advancement of *IT*. Decentralization, modularization, and automation of an ES helps to adopt the emerging *IoT*. IoT can be applied to support decision-makings at all of domains and levels of ESs, and an ES should be designed in a way that strengths of IoT can be fully utilized. In this paper, an automated system for assembly modeling of complex products is discussed.

To meet new requirements of an ES built upon IoT infrastructure, the object-oriented model template is proposed for the assembly planning. It inherits the advantages of object-oriented methods and product template methods. It is very appropriate to be applied in the distributed and decentralized environment. Objects involved in a product template are encapsulated, and this facilitates the reuse of assembly components and modularization of information systems. Additionally, the assembly modeling for a complex product has been automated. The system can retrieve assembly relational matrices automatically from *CAD* models of product, the assembly sequences and exploded views can be generated from the assembly relational matrices with little manual intervention. The algorithms for the contact and interference relation matrices have been discussed in details. The development of these algorithms have also motivated by the deficiency of existing methodologies in structure representation and information acquisition of assembly relation models. The proposed matrix ($\boldsymbol{M}$) for assembly relations integrates the contact relations and connection relations among functional parts and accessory parts. EM solves the problem that previous interference matrix could not be used to analyze the parts in arbitrary directions. The generation of assembly relation matrices is based on static interference analysis and the generation of EM is based on dynamic interference analysis. The developed assembly planning system can be interacted with the server with the UG NX CAD/Cam system directly, and it meets the requirements of decentralization, modularization, and automation for the adaption of IoT Infrastructure. The report work is preliminary; our further effort will explore cloud computing in supporting automated assembly modeling of complex products in a distributed design environment.

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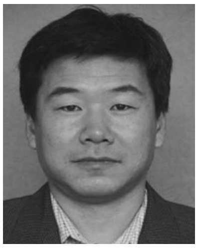

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