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An Automated Intelligent Feature-based Maintenance Plan Generation Method

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Abstract. Great efforts have been made to make maintenance processes intelligent and automated. Data analysis, assembly-disassembly sequence generation, maintenance optimization models and knowledge-based systems are some of the research areas related to maintenance with significant contributions. Until today, there is no robust plan generation method available for the scientific and industrial community. The available methods are mostly human-dependent and are lacking in automatically assist maintenance operators to perform maintenance tasks. This paper presents a method to create an intelligent system capable of automatically provide maintenance instructions at a product and component level using feature-based product identification. This paper introduced a framework that integrates different algorithms for a knowledge-based decision, robust reverse engineering, CAD (computer-aided design) model feature recognition, product identification, and maintenance plan generation. The method is able to identify the product from CAD files generated through the 3D points-cloud data. The identified product is then linked to the knowledge-base, which provides an intelligent plan for the maintenance procedure. The method not only provides a product level maintenance procedure but also generates the shortest path for proper inspection and repair at the component level. The automated and intelligent tool contributed by this paper supports the naïve operator to execute tasks efficiently without relying on their expertise. The method is generic and able to accommodate and integrate new modules to support other applications in the future.

Keywords: Maintenance Automation; Failure Mode and Effect Analysis; Repair; Disassembly; Reverse Engineering.
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1 INTRODUCTION

Maintenance is a labor-intensive industrial process that is still planed and performed manually. Currently, industries are aiming to automate as many industrial processes as possible to improve production and service, as well as industrial safety. For maintenance, the time taken to complete a preventive or corrective task depends on the operator's knowledge and experience. New maintenance operators are starting at industries with an entry-level experience every day. It takes time for them to be trained by experienced operators, which are not always available. Automating maintenance processes will help to solve these current problems. However, maintenance is one of the areas that represents a great challenge when it comes to automating the entire process. Planning and execution of maintenance tasks, for example, are still challenging to automate with the existing technology due to the complexity and level of difficulty of disassembly tasks. On the other hand, knowledge-based decisions are needed for maintenance planning to reduce downtime, which is a task currently done by experienced professionals.

There are some research areas that are contributing to improving maintenance processes. Many researchers have worked to improve specific areas of maintenance processes to make it more intelligent, efficient, safe and easy to perform. Even though it will take a long time to fully automate all maintenance processes, the development of a method, which is capable of autonomously generating maintenance plans and assistance during the process, represents a big step forward. The proposed framework (Figure 1) in this paper integrates different methods to support the maintenance process at the product and component levels. This will allow to address some of the existing challenges in industry, such as planning and execution for a maintenance tasks when new hires are involved. Entry-level maintenance operators will be provided with the maintenance procedures for the identified product as well as guidance during corrective maintenance. The framework is limited to provide existing maintenance procedures in the knowledge-base and suggested procedures from similar products.

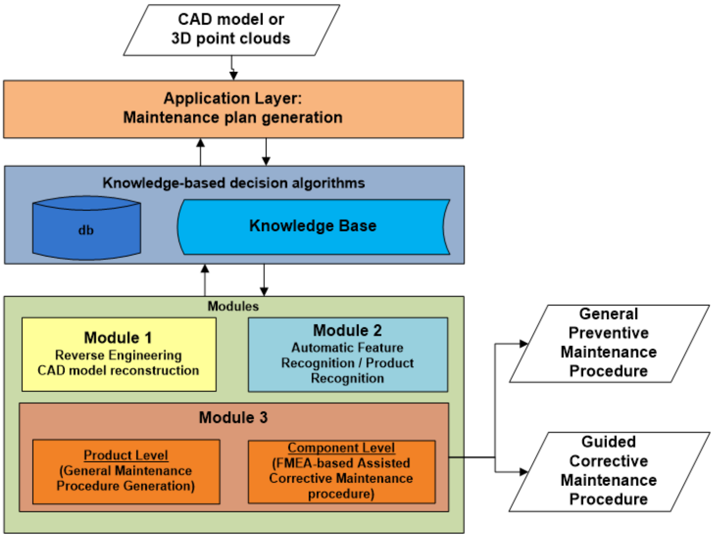

Figure 1: Feature-based Intelligent Maintenance Plan Generation Framework.

2 LITERATURE REVIEW

Many existing research integrates new existing tools and technologies to support maintenance processes. 3D scanning and reverse engineering are important processes leading to robust maintenance, which are research areas that are growing very fast. Some methods use 3D scanning to reconstruct the CAD model [9,22]. This has many advantages, one of them being able to 3D print the scanned product for different applications [12,25]. Another popular application of this technology is the mapping and inspection of systems on "as is" conditions [12,19,21]. These represent powerful and efficient tools for industries to make maintenance decisions. A reverse engineering method is presented to compare the actual condition of a real product against the original design model to ultimately plan for remanufacturing [11, 28-29]. Based on the difference between the two models, 3D printing and machining tasks are provided to restore the real product features and integrity. Even though there are numerous methodologies and applications for reverse engineering contributions, it has not been integrated to identify products and support maintenance processes.

Many research efforts have been devoted to addressing the surface fitting problem for reverse engineering. Fischler and Bolles [6] first introduced the basic RANdom Sample Consensus (RANSAC) which later became one of most well-known algorithms to detect surfaces from the data sets that contain noise and outliers. It is an iterative process that randomly samples a subset from the data points in each iteration to estimate the corresponding model parameters. Schnabel et al. [20] developed the basic RANSAC framework for primitive surface fitting (plane, spheres, cylinders, cones and tori). Li et al. [14] and Lee and Duan [13] developed the GlobFit method and the global 3D segmentation, respectively, to improve the robustness of the original RANSAC method by coupling local and global aspects of the fitting problem.

Automation has been the answer to many problems in industry for multiple processes [1] and for construction [16]. Maintenance planning scheduling for repair or inspections is one of the areas that is being automated to be able to complete daily activities with the available resources [23]. Likewise, other methods at the design stage automate a system that predicts the time taken to perform maintenance tasks to a product [15], which is a very important consideration when designing a product and changes can be made before it is manufactured. An even more automated concept is discussed to use the autonomous mobile robot to perform inspections in a production plant [7]. Even though these are good contributions to automate maintenance processes, there is a gap when it comes to automating maintenance intelligent planning and execution.

Knowledge-based systems have been applied to several methodologies supporting maintenance for many years. Some systems use Augmented Reality (AR) and/or Virtual Reality (VR) to provide support during maintenance operations [5]. Jo et al. [8] proposed a framework with a knowledge-base to support aircraft maintenance operations by displaying information and procedures related to the context of the real-time vision. Others developed a knowledge-based system to support maintenance operations at different organizations for building maintenance [18]. Planning [2] and maintenance decision problems are also being modelled with knowledge-based systems. One method integrates optimization models to make maintenance decisions in a given region with multiple concrete bridges, where available resources, criticality and impact on users are factors that need to be considered [3]. However, there is no knowledge-based system designed to replace the need for experienced operators for maintenance plan generation and assistance for execution.

The closest work related to maintenance plan generation, which provided maintenance procedure using image recognition, was presented by Cusano et al. [4]. Other efforts developed a vision-based system to inspect and detect the absence or presence of fastening bolts to take maintenance actions [17]. Lately, laser scan technology had been used for the road marks inspection and maintenance decision [26]. While these methods are great contributions to maintenance automation, they are focused on very specific cases and limited to 2D image recognition. They are also only capable of providing pre-defined maintenance procedures.

In each of these areas, there are gaps that represent many opportunities to make a great contribution to maintenance automation. First, reverse engineering methods have not been applied to maintenance planning and execution. Second, automation methods are still dependent on humans when supporting maintenance execution. Finally, knowledge-based systems for maintenance applications are still dependent on humans in order to save new knowledge. By developing an intelligent automated method combining different technologies to support maintenance processes, these problems can be covered. Our previews work presented a method of maintenance plan generation based on CAD model automatic feature recognition (AFR) [27]. The system is able to automatically identify a product from a CAD model and link it to a knowledge-base where the maintenance is provided or generated from existing procedures. However, more work is done to develop a new generic method, which integrates a module to recognize real products without the need for a CAD file and a component level critical path planning for an efficient maintenance procedure. The product is recognized from CAD models built using points-cloud data. The component level maintenance plan generation is introduced, where intelligent assistance is provided to the user for optimal disassembly sequence for inspection and repair. This new integration, driven by a knowledge-base, can assist operators to automatically identify the product, have access to the right procedure and be assisted in executing tasks in a safe and efficient manner. The proposed method is explained in the following section.

3 METHODOLOGY PROPOSED METHOD: FEATURE-BASED INTELLIGENT MAINTENANCE GENERATION (FIMP)

The framework is designed to support maintenance operators by automatically identifying real products, generate or provide the maintenance procedure and receive step-by-step guidance (if required) for corrective maintenance procedures at the product and component level.

First, CAD models and 3D points-cloud data are supported as an input to the system. The developed application for maintenance plan generation is linked to the knowledge-based decision algorithms. Three different modules are available and driven by the knowledge-base when required. A reverse engineering module is able to reconstruct the CAD model when the real product is 3D scanned to generate points-cloud data. Another module is an algorithm proposed in our previews work [23], which automatically extracts the geometric features of the model. Then, user-defined features (UDF) are searched on the CAD model extracted data to identify the product. Once identified, the product is linked to the knowledge-base where the maintenance information is stored. If the knowledge does not exist for a particular model, the last module is able to generate a new procedure from existing knowledge at a product level. The component level maintenance plan generation is another contribution of this paper, which assist operators in performing corrective maintenance path towards the defective component. Step-by-step guidance is provided to reach components with higher chances of failing for inspection and repair. The method proposed is a generic knowledge-based framework, which can allow other applications and new modules integration. The description of the proposed three modules, followed by the knowledge-based algorithms and developed application, are presented below.

3.1 Module 1: Reverse Engineering

Commonly, a mechanical component behaves as a property of having a limited number of primitives (regular shape). In this paper, our study is focusing on these mechanical products and a comprehensive reverse engineering method for CAD model reconstruction is used. This method enables a fast and accurate reconstruction from raw points-cloud to CAD. The flowchart of the proposed method is presented in Figure 2. First, 3D points-cloud is collected as an input through a laser or depth-cameras. Then, a random sample consensus (RANSAC)-based [20] algorithm is introduced to efficiently obtain parameters of primitives by the surface fitting. Modelling operations are performed depending on the topological relations of primitive surfaces to construct the CAD model. Finally, the CAD model is sent to the AFR module for product recognition. A brief description of the functionality of the RANSAC-based algorithm is as follows.

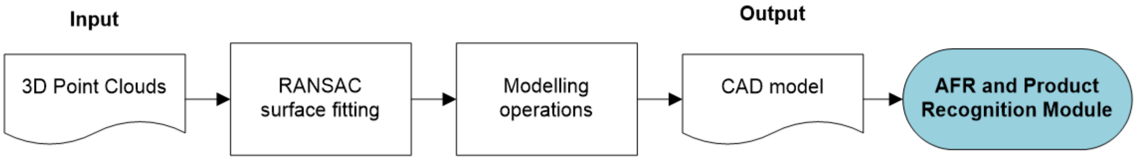

Figure 2: Flowchart of the proposed reverse engineering method.

3.1.1 RANSAC-based algorithm for surface fitting

The algorithm of the RANSAC-based method is presented in Algorithm 1. Input ***P*** is a set of point clouds. Output ***BS*** (Best Shape parameters) is a set of parameters of the best primitive detected.

Algorithm 1: RANSAC

Input: $\boldsymbol{P}$: a set of point clouds
Output: $\boldsymbol{BS}$: best shape parameters
$\boldsymbol{V} \leftarrow \mathbf{0}$: number of valid points
repeat
  1. $\boldsymbol{CS}$=rand($\boldsymbol{P}$) ;
  2. B=sum(d(CS,P_i)$<T$)
  3. **if** $B > V$ **then**
    4. $V \leftarrow B$;
    5. $\boldsymbol{BS} \leftarrow \boldsymbol{CS}$;
  end
until *Reach the maximum iteration times*;
6. $\boldsymbol{VP} \leftarrow$ record($\boldsymbol{P}$)

Step1: A minimal number of points, which enable to construct the target shape, are randomly selected from the points-cloud P to construct a candidate shape (***CS***).

Step2: Algebraic distance is calculated as the distance from points-cloud to candidate shape. The number of valid points (*B*) which have distances less than the pre-defined threshold (*T*) is counted and stored.

Step 3 to Step 6: The better candidate, which has more valid points, is accepted in iterations and the best candidate for target shape is kept until reaching the maximum iteration times. The parameters of best shape are stored in BS and the valid points (***VP***) for the best candidate have remained.

3.1.2 CAD model Reconstruction

The information on the surfaces of the model is obtained after surface fitting. A model operation is required to build a solid model based on the information obtained. In the conventional modelling method, CAD systems provide functions to create primitive solids such as block, cylinder, cone, sphere, torus and wedges. The parameters of surfaces obtained in the surface fitting process are used for generating their corresponding primitive solids. Basic Boolean operations are performed to construct the final model based on their topology relations. In our study, commercial CAD software was used for the modelling operation. For the purpose of this paper, any other reverse engineering commercial software can be adapted to the framework to achieve similar results.

3.2 Module 2: Automatic Feature Recognition and Product Identification

The product level method of this module was presented in the previous work [23]. The Automatic feature recognition is designed to extract all the geometric features from the CAD model (STEP file or Solidworks part file) to a database. After this, the fast searching engine of the database allows the system to look for UDFs, which defines the product. A key number is generated based on the features found from the product, which ultimately constructs the link to the knowledge-base. Depending on the case, the system is capable of providing an existing maintenance procedure for the identified product and able to create a new procedure in the next module using existing knowledge.

3.3 Module 3: Product Maintenance plan Generation

This module integrates a product level submodule and a component level submodule. The product level generates a maintenance procedure from existing knowledge. The system automatically finds a similar procedure that can be modified by the user and adapted for the new product. The case is saved and ready to be used in the future. Geometric similarities of the product are the main criteria used to provide existing maintenance procedures.

The component level submodule integrated is designed to provide guidance to operators specifically when performing corrective maintenance procedures. The system consists of step-by-step guidance to disassemble the product with real-time user interaction. A precedence graph for disassembly and the failure mode and effect analysis (FMEA) is used to generate an assisted disassembly sequence for maintenance. The risk priority number (RPN) from FMEA information is an indicator of the risk associated with the failure mode or component. The higher the RPN number, the more critical the component will be. In a given product, each component RPN value is ranked from highest to lowest. This rank number is used as a criteria to follow when making disassembly sequence decisions within a given precedence graph for the disassembly of the product using knowledge-base. The user contribution relies on the physical disassembly and inspection of each component. Depending on the user observation and action taken in every step, the method will guide the user until at least the most critical components (1st and 2nd most critical) had been inspected and a faulty component had been repaired or replaced including the most critical one. The reason for using RPN value is that there is a higher chance of finding faults in those components ranked first. If the FMEA information and disassembly precedence graph are not available in the knowledge-base, the system will provide information from similar products. The user can then make the necessary modifications and ultimately save the case for future usage. For the disassembly sequence precedence graph, the user is required to review and modify the suggested graph to match the information on the new product. This is done in a table where all components are listed along with the precedence relation to other components for disassembly. For FMEA data, each verified component name will be assigned to its corresponding RPN value and ultimately rank from the highest to the lowest.

3.4 Knowledge-based Decision Algorithm

The knowledge-base is designed to drive all the modules and make the decisions needed depending on each possible case. It automatically provides a maintenance procedure and also assistance to the operator for product identification. However, and more importantly, it is also capable of saving new generated knowledge automatically when a new case base is identified. The application layer allows two-way interaction between the user and the knowledge-base. A security check is integrated into the system in order to avoid unauthorized personnel from compromising knowledge integrity. Only authorized personnel are able to make modifications. For these reasons, the proposed knowledge-based system gets better every time as used. The database in this layer is used to store all the extracted information and is available to the system every time, if needed.

3.5 Developed Application for Maintenance

The user interaction with the system is done through the developed application, which is directly connected to the knowledge-base. Pneumatic valves are used in this paper as the product to prove the proposed method. The user interaction flowchart with the four different cases can be seen in Figure 3. For the case where the product is unknown and the CAD model is available, the AFR and product recognition module is called. In the event of using the reverse engineering module to construct the CAD file, the user is required to verify and make product measurement corrections as the standard points-cloud data doesn't count with product information as an original CAD file. The general product maintenance procedure is available to the user once the product is recognized. For maintenance procedure at a component level, the application shows the components and sequence to disassemble the product towards the most critical component (ranked 1st). Every disassembly direction is provided after the user inspects each disassembled component. Once the procedure is completed, repair time, failure mode, failure time and failed component are extracted and saved in the knowledge-base.

4 CASE STUDY AND DISCUSSION

To validate the proposed methodology, commercial pneumatic valves information, CAD models and maintenance procedures were used [24]. To run the experiments, commercial CAD software (Solidworks), database software Microsoft Access (MSA) and Visual Basic for Applications (VBA) were used. The framework is tested using a standard Windows 10 computer with Intel Core i5-6400 CPU and 12 GB RAM. The graphical user interface (GUI) for the developed application "intelligent maintenance plan generation system" is described next.

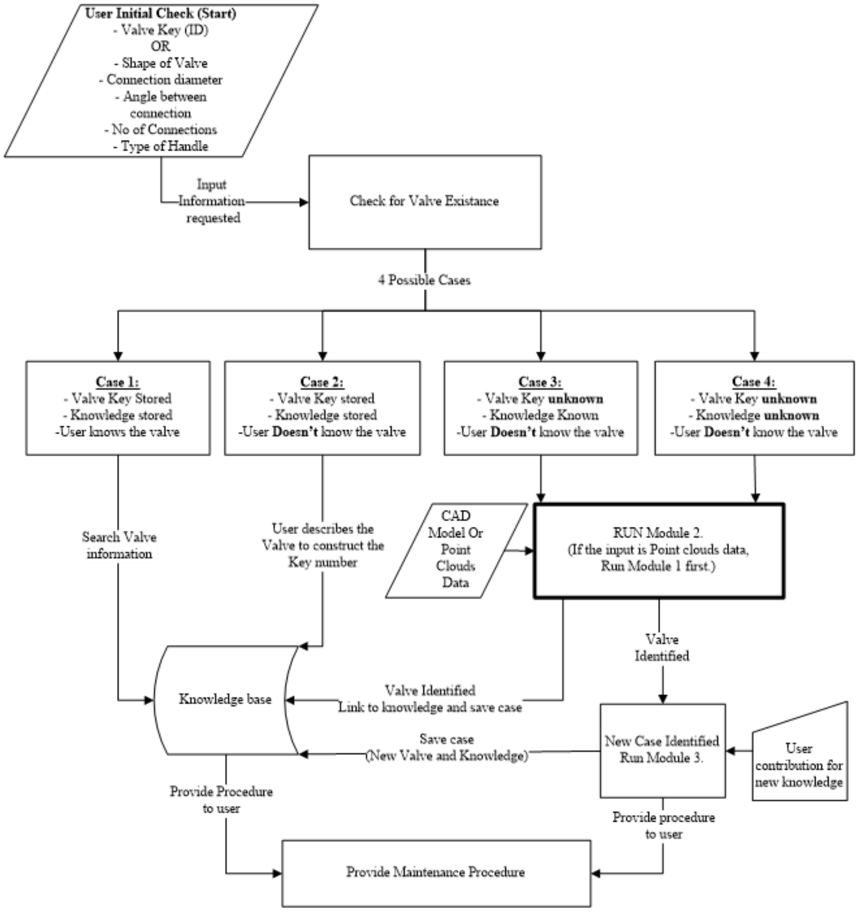

Figure 3: Feature-based intelligent maintenance plan generation flowchart.

4.1 Developed Application for Intelligent Maintenance Plan Generation (GUI)

The Application for user interface consists of two main MSA forms: "The initial Questionnaire" form and the "Intelligent Maintenance Plan Generation System" (IMPGS) form (Figure 4). The first form consists of a set of option buttons where the user is expected to answer all the questions made to address the different possible cases. Figure 4(a) represents the case where the user knows the key number of the product. Figure 4(b) represents the case where the user does not know the key number and multiple-choice questionnaire is provided to identify the product to describe it. These are: shape, number of connections, connection diameter, type of handle and angle between connections.

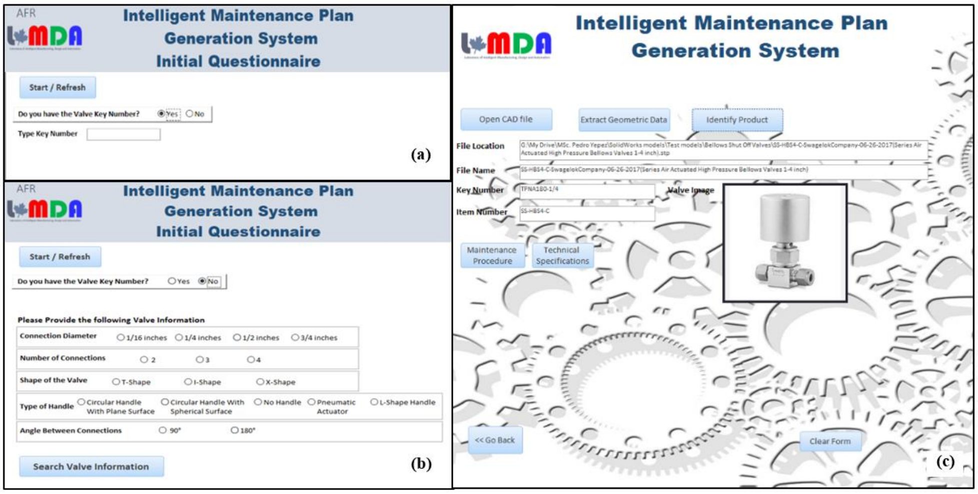

Figure 4: Graphical User Interface: a) Initial Questionnaire: Key number known b) Initial Questionnaire: Key number unknown c) IMPGS form.

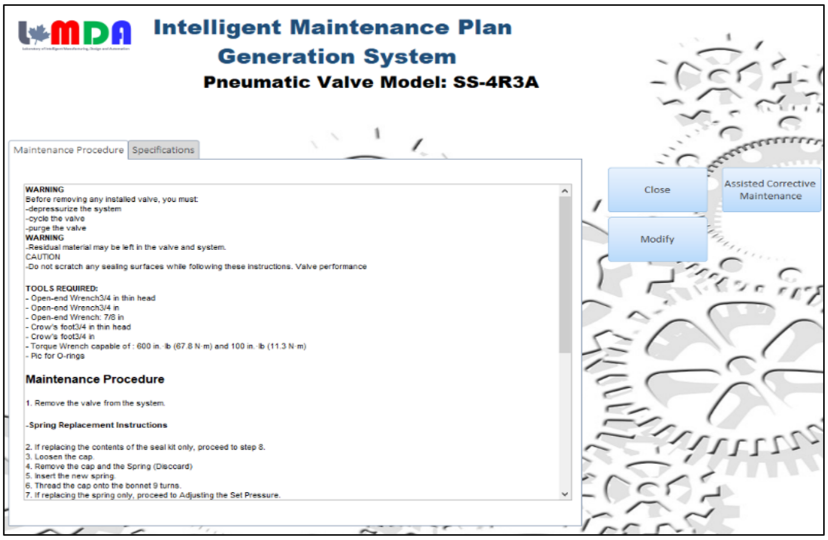

Figure 5: Product Maintenance Procedure and Technical Specifications view.

The second form appears to the user once the case at the initial questionnaire is detected. If the product identification is required, a button to open the CAD file is shown, which is linked to the CAD software as it automatically opens the exploration window to find and select the CAD model to be identified. Once this step is completed, the "Extract Geometric Data" button appears and upon clicking, the required information data is downloaded to the database. Finally, a third button, "Identify Product", appears to initiate the product identification. File location address, file name, key number and manufacturer's item number can be displayed once the product is identified. In addition, the "Maintenance Procedure" button, "Technical Specifications" button and product image are shown to the user. These same options are shown to the user if, at the initial check, the case exists in the knowledge-base. Each maintenance procedure is presented in a template form for each product (Figure 5). Every template has two tabs: Maintenance Procedure and Product Specifications. This information can be modified. However, as mentioned before, it is limited to authorized users. There is also a "Corrective Maintenance Assistance" feature, which will trigger the component level submodule to assist operators. For cases where the procedure does not exist in the knowledge-base, the system will provide similar procedures in an editable form subjected to user modifications. Finally, the buttons to save all the modifications done to the existing procedure and save new cases are displayed.

4.2 Case Studies

In order to validate the method and system, few commercial pneumatic valves have been selected for product recognition and intelligent maintenance generation. Three pneumatic valves in Table 1 were selected to demonstrate three different cases.

Case #	*1*	*2*	*3*
Valve Class	3-4 Way Ball Valves	Relief Valves	Bellows Sealed Valves
Class usage	Meet your system needs with the broad range of Swagelok ball valves made in a variety of styles, pressure ratings, materials, and end connection choices, configurable for a variety of applications.	Obtain over-pressure protection for a variety of applications with Swagelok proportional relief valves with easy external set pressure adjustments.	Isolate system fluids and achieve reliable, leak-tight performance with Swagelok bellows valves that use a packless design and a welded seal. Bellows valves are ideal for applications where the seal to the atmosphere is critical
Series	4 way - 40 Series	R3A (Proportional pressure relief valves)	BN4 (bellows sealed)
Connection Size	1/16 inch	1/4 inch	1/4 inch
Image			

Table 1: Pneumatic valves for case studies [26].

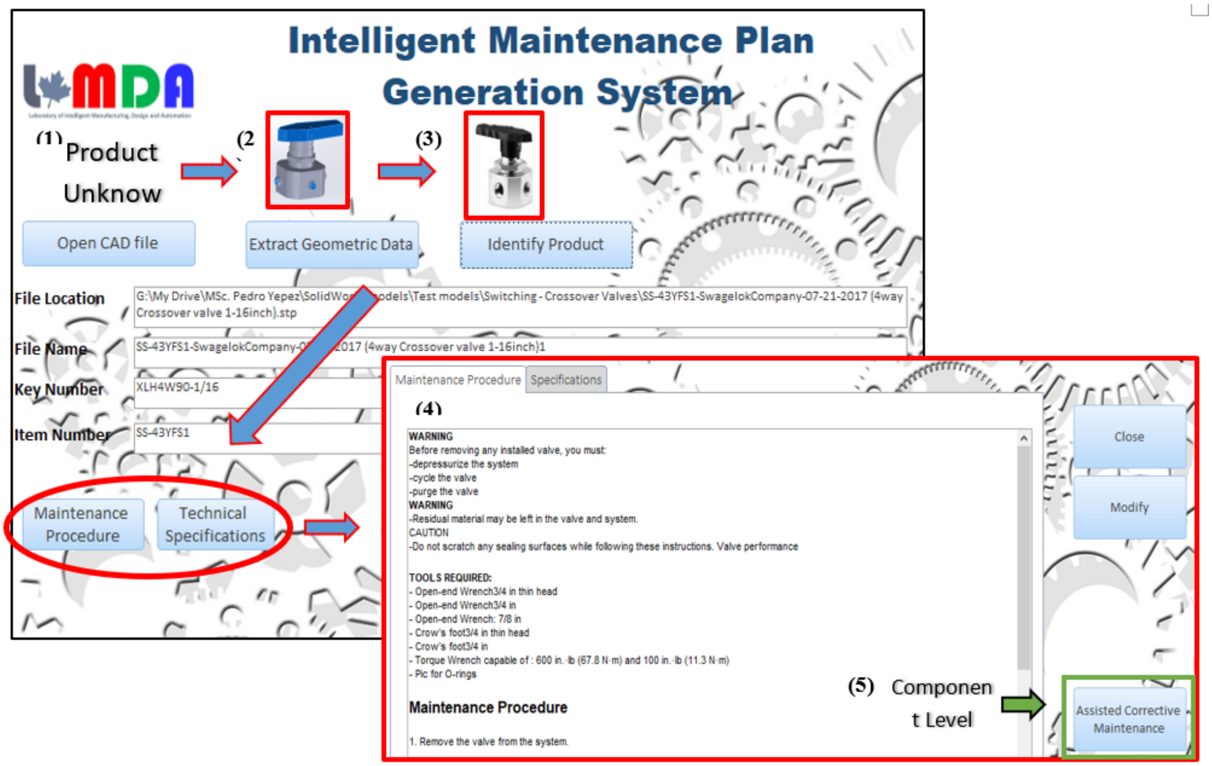

Figure 6: Case study 1: (1) Open CAD file (2) Geometric feature extraction (3) AFR and product identification (4) Maintenance procedure and specifications provided to user (5) Maintenance assistance at a component level.

4.2.1 Case 1: Product does not exist in the system

The product is unknown to the user and to the system. The CAD model is available, but the general preventive maintenance procedure exists in the knowledge-base as well as the disassembly sequence and FMEA information. The first step for the user is to fill the questionnaire form (Figure 4b), where the key number or a geometric description is required. In this case, the user describes the pneumatic valve as followed: 1/16 inch connection, 4 connections, X-shape, L-shape handle and 90° between connections. Since the product is also unknown to the system, a CAD model is requested to identify it. In Figure 6 step (1), the CAD model is opened in a STEP file which is a standard commercial shareable format. In step (2), geometric features are extracted to the databased and finally the product identification button searches for UDF, which defines the valve and creates a key number in step (3). The recognized product is linked to the knowledge-base through the generated key number. Now the Maintenance procedure and technical specifications buttons are available to the user along with a visual image of the product in the IMPGS form. On click, the maintenance procedure is shown to the user in Figure 6 step (4). The Assisted Corrective Maintenance provides guidance to the user in a case where the product has failed and assistance to find the fault component is needed, as shown in step (5). The integrated disassembly sequence in the form of precedence graph with the FMEA RPN ranked values will take the user to the fastest path to reach the most critical components, where the chances of finding the failure are higher. As explained in section 3, the assistance terminates once the fault component has been found, repaired/replace and at least the most critical component had been inspected. However, the user has the option to continue to disassemble the whole product for a complete inspection if resources are available (Figure 9).

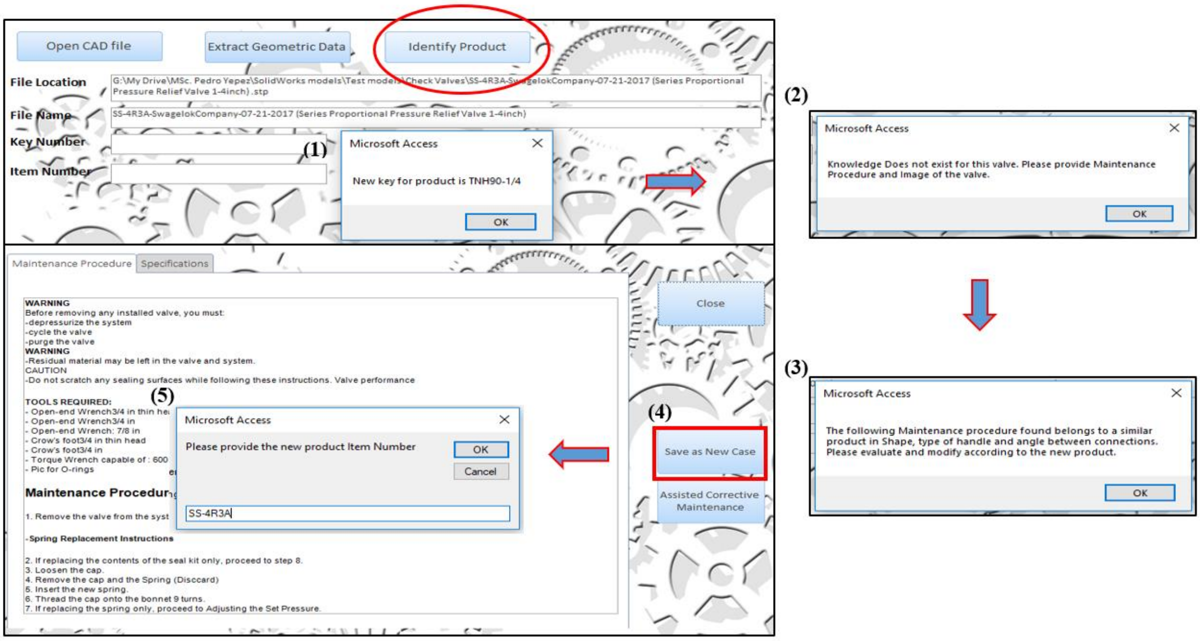

Figure 7: Case study 2. (1) Key generated for new product (2) Knowledge does not exist (3) Similar maintenance procedure will be provided (4) User can modify the similar procedure and save as new case (5) Confirm the new product item number after new case is extracted.

4.2.2 Case 2: Product and Knowledge unknown to the system

CAD model again is available, but the product is unknown to the user and does not exist in the knowledge-base. The system in this scenario provides a similar procedure to build a new case and save it for future usage. First, the user will again describe the product geometrically in the questionnaire form (Figure 4(b)). Since the product is unknown, the geometric feature extraction and product identification are made to generate a key number as seen in Figure 7. The system finds that the key number does not exist in the knowledge-base in step (2), therefore a similar procedure will be provided to the user in steps (4) and (5). Geometrical similarities for existing products in the knowledge-base are searched to provide similar maintenance procedures. The existing procedure belongs to product named “2B”. As seen in Table 2, both products have the same shape: no-handle feature, the same number of connections and the same angle between connections. The user has the option to modify the suggested maintenance procedure and specifications to fit the new product.

At the component level, the user will have access to the suggested procedure. Since the corrective maintenance is automatically provided from the FMEA and disassembly sequence precedence graph, the user can check and modify each information of the suggested product (Figure 8 and Table 3). Once all this process is done by the user, the maintenance procedure form for the new product can now be saved as a new case (Figure 7, steps 4 and 5). At the end of the process, in future cases the product is known and the maintenance procedure and specifications can be provided to the user without having to identify the product again or looking for similar products.

Product	*2*	*2B*
Series	R3A (Proportional pressure relief valves)	R4 (proportional pressure relief valves).
Connection Size	1/4 inch	1/2 inch
Description	New identified product	Existing product and procedure
Image		

Table 2: New product vs existing product. [26]

R4 Series	
C1	---
C2	*C1*
C3	*C2*
C4	*C2*
C5	*C4*
C6	*C3*
C7	*C8*
C8	*C9*
C9	*C10*
C10	*C6 and C11*
C11	---

Table 3: Existing Precedence table for disassembly of product 2B.

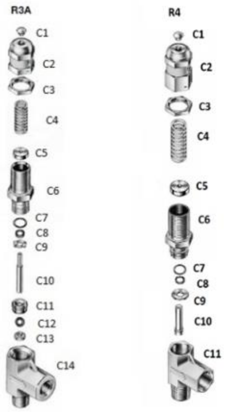

Figure 8: Exploded view of the new valve (R3A series) vs existing valve (R4 series) [25].

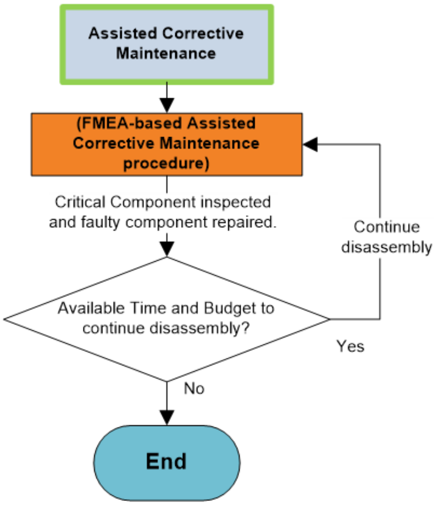

Figure 9: Corrective maintenance flowchart.

4.2.3 Case 2: Product and Knowledge unknown to the system

For the third case, the CAD model is not available, therefore reverse engineering module is used to reconstruct the CAD model and identify the product. The maintenance procedure and technical specifications exist in the knowledge-base. Once the user has been prompted that the product is unknown to the system and the CAD model is not available, it is required to 3D scan the product. This will generate the raw points-cloud of the product. The RANSAC-based algorithm in module 1 performs the surface fitting (Figure 10(b)) to ultimately reconstruct the CAD model. The product in the three stages of the reverse engineering process is shown in Figure 10 (a, b, and c). The final CAD model is then opened through the system to extract the geometric features and identify the product. The user is asked to declare that the product was 3D scanned, and then make corrections to the connection diameter of the valve. A new key number is generated and the knowledge-based decision algorithms provide the existing product information to the user. The sequence can be seen in Figure 11 (steps 1 to 5).

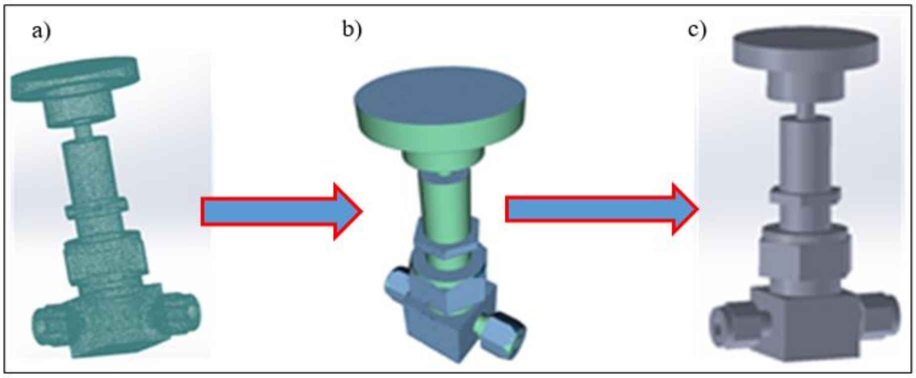

Figure 10: Reverse engineering process: a) points-cloud data, b) surface fitting, c) reconstructed CAD model (STEP) file).

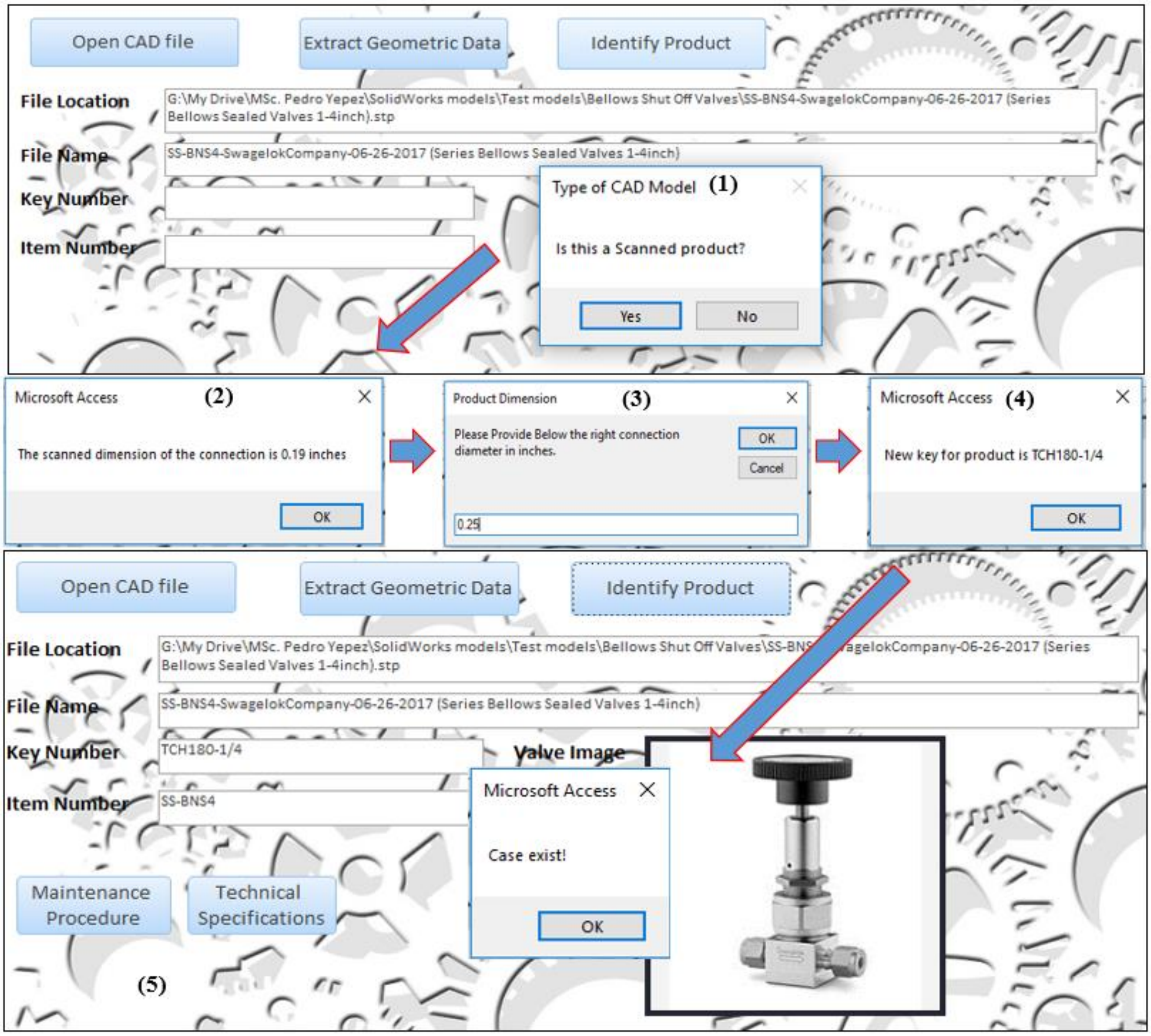

Figure 11: Case study 3, (1) Type of input file (2) Scanned dimension (3) Correction of connection diameter (4) Key for identified product (5) Existing maintenance procedure provided for the identified product.

4.3 Discussion

For the three different cases, the system is able to identify the product and link it to the knowledge-base. It is also able to generate new cases from existing knowledge, which makes it able to learn and get better in time. The ability to provide maintenance procedures from 3D points-cloud improves the flexibility of the system, which becomes very useful for the scientific community and practical purposes, where CAD models are not always available. On the other hand, the system proves that it can either provide general product level maintenance procedures as well as a component level maintenance procedure. This particular case solves the repair time problem when having new operators executing these tasks. At the same time operators are in a way being trained by following the provided procedures which will later result in efficiency improvement. The system is designed in a way that can support other applications in the future. New modules can be integrated into and used to support the new application along with existing modules and knowledge-base.

The developed application is limited to work with a sample of pneumatic valves. New UDF needs to be defined in module 1 in order to support other products. On the other hand, the assisted corrective maintenance procedure can only achieve the shortest path within the existing disassembly precedence graph. Further work can integrate existing models to actually generate an optimal sequence considering cost and time for disassembly.

5 CONCLUSION

The developed method proves that it can become a powerful tool for improving and automating the existing maintenance processes. In general, it integrates different technologies such as the RANSAC-based reverse engineering method that, in the past, were not applied to support automated maintenance planning and execution. More specifically, it helps to solve maintenance execution time and knowledge needed when non-experienced operators are recruited. The proposed method can assist them by automatically providing the proper procedure and step-by-step guidance for corrective maintenance if needed. It works by simply recognizing a product from a CAD model. For those cases where the CAD model is not available, the system is able to process 3D points-cloud to reconstruct a CAD model and ultimately identify the product to generate a maintenance plan. This methodology is validated to support solutions in three different scenarios: unknown products to the user and system, unknown maintenance procedures and unavailable CAD files.

Future work will focus on integrating more technology and methodologies to support maintenance processes such as augmented reality, virtual reality and optimization models for fast product disassembly. In addition, further complex applications can be developed and validated through the framework to support its knowledge-base. The reverse engineering module is able to recognize the UDF and define the product. However, since the points-cloud data is not as precise as a CAD model in terms of dimensions, the user is required to provide the exact connection size when the product is being identified. This requested input ultimately makes the link to the knowledge-base possible. In addition, for RANSAC-based method, the user must set the different thresholds for the different surface fitting. As the consequence, the results are not robust for different models, especially for the noisy data. Therefore, a future work can be outlined as using a more robust reconstruction method in the first module of this study.

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