Abstract—The correct planning of the assembly or disassembly of a product is of great importance for many aspects of a product such as its final cost, its impact on the environment or the number of hours that it can be used. We present a method for the automatic and fast generation of part precedence information for the planning of assembly and disassembly sequences of a complex product, based only on the geometric representation of a product. The information generated by this method can be applied to a variety of applications that covers a great part of the life cycle of a product.

I. INTRODUCTION

CAD applications allow the development of geometrically complex products (see Fig. 1). However, the usage of these tools is often limited to the design of a product while the analysis of other problems such as the design of the sequence for the assembly of the product is done using physical mock-ups [1]. The increase in computer power, of even commodity hardware, enables the application of computers to tasks such as the geometric analysis required to automate the generation of assembly or disassembly sequences.

The advances in these technologies, such as the increase in graphics processing power, have enabled the development of interactive tools that help designers in the analysis of product design [2]. These advances allow the analysis of a product using a virtual view of the whole lifecycle of the product, in what is called a virtual factory [3].

Most products are composed of multiple components that must be assembled. For complex products, the definition of a correct assembly sequence can be difficult. In this case, the addition of an automatic assembly planner to a simulation and design environment can provide engineering teams with useful hints and alternatives.

Environmental concerns [4-6], also require the development of procedures that allow the partial or complete disassembly of a product, either to allow the classification of the components or to extract parts that contain environmentally-hazardous materials. Disassembly data can be used for the evaluation of the environmental impact of a product [7].

Disassembly planning can also be applied in the planning of maintenance operations. In this case the objective is usually the removal of a single component that must be substituted or revised.

However, it is important to note that the impact of these techniques is not limited to the design of the assembly or disassembly processes. The information generated during the planning of these activities can have a great impact on other phases of the life cycle of a product. For example, the automatic planning of assembly and disassembly tasks can be used during the design phase to assert the design and to detect design errors of the product that would lead to components that cannot be properly maintained or assembled. In this phase, it can be also valuable as a mean to evaluate different product designs.

An assembly or disassembly sequence can be defined by the precedence relationships between the different components of the product [8]. This paper presents a simple and fast method for the automatic generation of this precedence information. Compared with other works in bibliography the method is not limited to a single set of predefined extraction directions and can deal with complex extraction routes using advanced path planning algorithms.

The rest of the paper is devoted to the analysis of this problem. It presents an overview of relevant related works in section II. We describe our disassembly method in
section III. Section IV shows a series of applications and future work that can be performed using the basic information obtained using the disassembly algorithm. Finally in section V, we present the conclusion obtained in this work.

II. STATE OF THE ART

Problems related with assembly and disassembly planning have been thoroughly analysed during the past decades. Early works on assembly and disassembly sequencing planning problems started at the end of the decade of the 80’s and early 90’s [8]. Most of these works were mainly focused on the problem of assembly planning for its application in the robotics field. The initial motivation was the generation of information for the automatic planning of assembly procedures in robotic workstations.

The works on disassembly planning and other related techniques can be divided into two main broad groups depending on the specific type of the input information used. In component based planning this information is based on the description of the components of the product by means of its geometry, contact information, behaviour, type, etc.

Some of the first works were based on the idea of recursively partitioning the assembly into subassemblies [13]. In a component based planner the algorithm is usually divided into two subproblems: the localization of a direction which allows the local translation of the components; a second step that validates this extraction direction by checking if the generated path is collision free.

Most of the previous work on automated assembly and disassembly planning has focused on complete disassembly with little investigation of techniques of selective disassembly [14]. In that work the authors propose a method that detects which parts of the assembly block the extraction of part along one direction of a fixed set of potential directions. The systems proceeds outwards detecting which parts block the removal and so finding the precedence relationship among the parts.

On the other hand, product based planning uses a more abstract information describing the product, such as the precedence relationships of the process, as input. An algorithm processes this information to obtain an optimal sequence under a given set of criteria. A survey on disassembly planning presented by Lambert [9] focuses mainly in papers that base the sequencing problem on the product.

One of the most widely used techniques for sequence optimization is Genetic Algorithms (GA). These algorithms try to resolve complex optimization problems with an approach akin that of natural selection in biological species [10, 11].

Marian et al. [12] provide an excellent review of the assembly planning process and the issues that arise from applying genetic algorithms techniques to solve this type of problem, such as the genome codification and definition. The authors use a modified wave propagation mechanism for the generation of random valid assembly sequences that enter the genetic algorithm process.

The complete planning process of selective disassembly involves not only the generation of correct disassembly sequences, but other factors such as tool changes, disassembly movements, part extraction paths [6], selection of transportation and grasping tools, set-up requirements, times, robot programs [15], accessibility analysis and ergonomics [16], etc.

III. METHOD DESCRIPTION

The method proposed in this article can be used to generate disassembly sequences. However, it is easy to adapt its output to generate assembly sequences, simply by inverting the order of the operations. The method uses as input a geometrical representation of the product, and therefore it falls in the category of component based planners. The method is based on two basic premises:

1) At least one part or assembly can be removed from the assembly at any time.

2) If a part cannot be removed from the assembly it means that there is at least one other component that blocks its removal path.

In this context, a part is considered removable from the assembly if there is at least one collision free extraction path that when followed by the component takes it outside the assembly. This implies that for every part tested a path planning problem must be solved. The path planning problem has been thoroughly studied in bibliography [1, 17]. However, due to the extreme complexity of this problem, the system uses, by default, a simplified planning system based on single translations.

The method contains two main steps. The first step is a pre-processing of the virtual mock-up. The main goals of this step are the generation of a spatial partition of the scene and the determination of the contacts among the different parts. The spatial partition helps in this second goal and provides support for other algorithms such as collision detection.

The second step is the proper disassembly process. The method starts by trying to remove parts from the assembly. As mentioned above, to detect if a part is removable the method tries to generate a disassembly path that links the assembled position of the component with the exterior of the assembly.

In every step, the system tries to find at least one component removable from the assembly. The first components extracted are, therefore, those that are not blocked by others. Furthermore, the removal of these
components can make parts that were initially non-removable to become removable. In following steps, these parts are detected when the system finds a valid extraction path for them.

To detect the parts that blocked the removal of a component, the algorithm tries to detect the interferences that would be caused by these obstacles if they were present. With this goal, the system makes the part follow the extraction path but with any component previously removed in its original position. The parts with which the component intersects are those that blocked the motion, and therefore those with which it holds a precedence relationship. In the case of single translation based path planning this procedure can be efficiently implemented using the graphics hardware of the computer.

Contrarily to other works such as [14], the method proposed removes components from the outside of the assembly to the interior. Proceeding in this way, we avoid having to define a fixed set of extraction directions. In our case, the extraction directions are computed from the contacts of the components, and therefore parts can be extracted along any direction.

Furthermore, the method by itself is not limited to using a single translation base path planner. More complex path planning techniques can be used to test if a part is removable from the assembly. However, the complexity of path planning makes the usage of a general path planner less attractive from the point of view of the global performance of the method.

In the case of the assembly of Fig. 3, the system can select any component as potential candidate for extraction, for example the lever. This component is not removable, and therefore, the system would proceed to test another component. Proceeding so, the method would identify the nut, and lid bolts 1 to 3 (see also Fig. 2) as directly removable components. After the removal of these components the method would continue and, in the case of the example, the lever would be detected as removable from the assembly. For this component, a simple translation extraction path is a straight line moving upwards. The system would use this extraction path to check if there is any previously removed component that intersected with the lever when it moves along its extraction path. In the case of the example, the nut blocks the extraction of the lever and, therefore, a precedence relationship can be established between these two components, as the removal of the lever requires the previous removal of the nut.

A precedence graph stores these relationships as a directed graph, where nodes represent each component of the assembly and a directed arch joins two nodes with a precedence relationship. The arch points from the node whose removal is required to perform the extraction of the second component which is pointed by the arch (see Fig. 2).

A simple depth-first search algorithm can be used to generate a valid disassembly sequence. For example, to remove the lid, the removal of the lid bolts 1, 2 and 3 is required. Also the removal of the lever is required, but to disassemble this component, it is necessary to remove the nut previously.

The selection of any component as a potential extraction target generates a big number of false tests that can be

Fig. 3. Detail of a Butterfly valve. The removal of the cover requires first the removal of the nut, the lever and three bolts (one is occluded).

Fig. 2. Partial precedence graph for the removal of the Rod from the Butterfly valve, automatically constructed from the geometry of the model.

Fig. 4. An instantaneous representation of the disassembly cache for the removal of the gray part along the two potential extraction directions.
reduced by using some heuristic. One extremely simple heuristic that improves the performance is selecting the components by its size. Effectively, in most assemblies it is more probable for a small part, such as a bolt, to be directly removable, than for bigger components.

A usual situation during the removal test is the retest of a part whose connections have not changed. This situation arises when the part selection criterion selects as a potential candidate a part that cannot be removed from the assembly. For example in Fig. 4, the first heuristic proposed favours the selection of smaller parts as candidates. In this case, this means the selection of the grey part. However, this part is not removable, neither using single translation nor using a complex path planner and therefore every removal test would fail.

To avoid unnecessary operations, especially time consuming operations such as path planning, when the method uses a single translation path planning strategy, it stores the results of the interference analyses into a cache (see Fig. 4). Using this strategy the method locates different potential removal directions using the contact information of the part (the arrows in Fig. 4) then it tests if the part can be removed along that direction. The method detects any obstacle along that trajectory. For every direction tested, the system stores a map that relates the direction with the obstacles.

If the part is going to be tested again using the same extraction direction, the system checks which parts were obstacles along that direction. If no obstacle components have been removed, the system does not test any further. In this case, the same conditions that disallowed the removal hold, and therefore, the part is not removable. On the other hand, if at least one obstacle part has been removed the test is performed again and the data in the cache is updated.

The usage of this simple cache enables the reduction of the execution time of up to a 80% depending on the model.

A third heuristic is based on the idea that components located near the exterior of the assembly are probably easier to be removed. A spatial partitioning is used to locate the objects on the exterior of the assembly, these are used as candidates. Two partitioning schemes have been tested: voxels and octrees. The usage of this technique also reduces the execution time in about 30-80%, with better performance for the octree based space partition.

The method is general and can be applied to the generation of removal precedence for a complete product. However, the basic method is also capable of generating selective disassembly plans, by simply stopping the search when the target component for the selective disassembly is found (see Fig. 5). The generation of this graph can be stopped once the system detects that the target component has been removed. This procedure generates an incomplete graph, which can be used to generate the disassembly sequence to remove a single target component.

IV. APPLICATIONS AND FUTURE WORK

The proposed method produces two different types of output. First, as we have seen, it produces a graph that stores the precedence information for the removal of the components. On the other hand, the system also produces the removal routes of the different components. Both of these two types of information are useful for a series of applications.

In this section we would like to propose some applications and potential future research lines, both for our planner and for other assembly/disassembly planners.

A. Generation and analysis of selective disassembly sequence for maintenance or recycling

In these applications there is a component targeted for its removal from the assembly. The motivations for this removal in maintenance operations are usually related with the change of an obsolete or defective part for a new one. However, this problem also arises in the planning of product dismantling for recycling, where only a given component of the product is targeted for removal, for example because it contains environmentally hazardous products. In these applications the use of a selective disassembly planner strategy can generate a partial disassembly precedence graph that serves to detect other parts involved in the operation.

An interesting field for the application of this technology is the development of augmented reality software for the dynamic assistance on maintenance tasks. In this application a user would use some kind of mobile device, such as a tablet PC or a PDA, and a camera. Once the system recognises the working environment it could generate an automatic disassembly plan augmenting the real image.

B. Optimization of assembly sequences for the construction of a product

Contrarily to the selective disassembly planning problem, this applications generates the complete...
disassembly of the whole product. In this case, the
dependence relationships obtained by performing a
disassembly must be reversed to generate an assembly
dependence graph. The extraction routes are also inverted
to become assembly routes.

As we have view in section II, many assembly systems
search an optimal sequence, starting from a description of
the precedence relationships of the product. Our planner
provides automatically this type of information and
therefore its output can be used as input for those methods.
For example, a GA can be used to search for an optimal
assembly sequence that generates random solutions based
on the information encoded in the precedence graph.
Additional information can be added to the information
generated by our planner to provide the optimization
algorithms with more clues about the nature of the process
analysed.

C. Generation and validation of other planning
activities: tool usage, grasping, ergonomics, etc.

The results obtained by applying the disassembly
procedure can also serve as input for other planning
problems in the design and organization of a fabrication
process.

Fig. 7. The usage of a wrench to remove a bolt requires a minimum
workspace. The automatic disassembly provides the minimum workspace
when only geometrical constraints are taken into account.

The decision of which tools (see Fig. 7) must be used to
perform an operation is usually dependant of the available
workspace. The analysis of the selective disassembly data,
allows the determination of the minimal set of components
that need to be removed from an assembly for the target
component to become removable. Therefore, the space
available will be limited by the number of elements
removed to access the component. An accessibility analysis
can start by using this minimum volume, then simulate the
operation and check if any other part blocks the usage of
the tool. In this case, the disassembly precedence graph
should be updated adding as dependencies the parts that
need to be removed prior to the use of the tool.

An important issue in the planning of any assembly or
disassembly tasks is grasping. At some point, a worker or a
robot must select a component and grasp it to perform an
operation on it, for example, to extract it from the
assembly.

This problem can be defined as: given a part or a tool
select the best grip position for the hands of a worker or of
robot (see Fig. 6). The exact definition of this problem
requires some way of measuring the comfort of the worker,
and the danger of producing injuries. This problem can be
viewed as a motion planning problem where the final
position is not given but is controlled by the gravity and the
potential motion of the part or tool.

Fig. 6. Grasping is especially important for some tasks.

Research on grasping has been performed mainly for the
control of robotic hands. For example in [18], the authors
present a heuristic algorithm to obtain the grasping for a
collision free motion of a three fingered hand and a robotic
arm. The algorithm divides the problem into two sub
problems one for generating the grasping position of the
hand and another that positions the hand using the DOF
of the arm. As the hand uses only three fingers the forces
exerted on the object always form a plane. The authors
present several heuristic techniques for reducing the
computational times.

Real-time solutions are achieved by reducing the
problem to 2D polygonal models [19], for a 3-fingered
human-like robotic hand. An optimal grasping solution is
not obtained since other criteria such as security can be
involved. In humans the grasping of an object is also a
matter of preference and not an optimal search. In human
hands several grasping attitudes can be found [20] which
makes the planning of this tasks more difficult. Also the
existence of various contact types during the approach
process of the grasping affects the dynamic model of the
robotic hand [21].

Again the disassemble precedence information provides
the minimum available workspace to perform the grasp.
However, in this case it can be of more importance the
information about the extraction route, since the grasp
should guarantee its stability all along it.

Finally, an important issue that arises in manual
assembly or disassembly planning is ergonomics. In this
case a human model is used to study the physical
requirements that a worker needs to follow to perform an
activity. The obtained dependencies and extraction routes
provide the work space available for the worker as well as
the accessibility constraints. These constraints can be
analysed to detect potential problems in the process.
V. CONCLUSIONS

In this paper, we have presented an automatic scheme for the determination of the precedence relationships of the disassembly of a product. This method only requires the geometrical description of a product as its input. The process is based on the ordered removal of components from the assembly and the analysis of their extraction paths to detect the precedence relationships between parts. The proposed method uses by default a single translation based approach for the generation of the disassembly paths. However, more general motion planning techniques have been used with success for complex extraction paths.

We have implemented several heuristic strategies to accelerate the disassembly process, such as the spatial location of the components or their logical state in the process.

The proposed method has been applied with success to several synthetic and real world examples. The method is capable of completely disassembling a 70 part model in less than 2 minutes using a standard PC.

The generated precedence information can be exploited in several industrial applications, some of which have been presented in the paper, such as, the generation of disassembly sequence for maintenance operations or recycling, or as support for other planning problems such as tool selection, grasping and the ergonomic analysis of the operations.

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