INTERNATIONAL CONFERENCE ON ENGINNERING DESING
ICED 05 MELBOURNE, AUGUST 15-18, 2005

IMPACT OF VIRTUAL REALITY SIMULATION TOOLS ON DFA AND PRODUCT DEVELOPMENT PROCESS

Alexei Mikchevitch, Jean-Claude Léon, Alexandre Gouskov

Keywords: Analysis, assembly, complex systems, design, virtual reality

1 Introduction

Product development focuses now on Concurrent Engineering aspects. This requires the consideration of all skill constraints contributing to the product life cycle: mechanical design, manufacture, Assembly/Disassembly (A/D), ergonomics, etc. To this end, DFX (Design For X) methods have been developed [1, 2, 3, 4, 5, 6]. Usually, the A/D studies based on DFA (Design For Assembly) software tools have a semi or fully automatic character and allow a quantitative assessment of the product from an A/D point of view. Moreover, such aspects as diversity and complexity of parts and A/D operations, fast and direct multi-criteria optimizations during the design, etc. are hardly considered using current DFX methods. In order to help the designer analyze the A/D or maintenance process of a product as well as to ease decision-making, new methods based on a direct assessment of a human being throughout the A/D operation simulation have been recently developed [7, 8, 9, 10, 11]. Thus, a method discussed in this paper is based on Virtual Reality (VR) tools used in the A/D and design contexts. Hence, various approaches for A/D analysis are discussed in the present paper. To this end, the interest of the use of VR tools for qualitative/quantitative A/D studies of complex systems for collaborative design, the possible use of virtual simulations during different phases of the product development are showed. Virtual A/D assessment methods are particularly interesting in the case of A/D analysis of complex mechanisms containing deformable parts as presented in this paper. The proposed method is illustrated by different examples of A/D tasks to demonstrate an impact of the use of VR tools on the development of DFA and design analysis methods.

2 Automatic DFA methods

The aim of automatic DFA methods is to allow the designer to improve quickly, quantitatively and automatically a given product from the A/D point of view. Thus, the coupling simulation/evaluation A/D system and CAD tools is often required. This allows extracting automatically geometric data necessary for A/D simulation from CAD models of the product. Generally, automatic A/D methods aim at minimizing the number of components and reducing the assembly cost, allow evaluating the assemblability of the product and producing an A/D sequence [1, 2, 6]. For example, according to some DFA methods, the reduction of the number of parts and assembly costs achieved through part standardization assuming that the complexity of systems and the A/D sequence time are proportional to the product part number. From the DFA point of view, the removal of some components could allow [1]: reducing the A/D time and cost, decreasing the use of special assembly tooling, reducing the failure probability, improving the quality, simplifying the product, etc. Thus, the automatic methods produce different quantitative information and recommendations about the product studied from various input data and criteria enumerated above.

Concerning the A/D sequencing problem, the A/D sequence generation represents a simulation usually subdivided into the following stages [1, 5]: product modeling, determination of component's mobilities, production of A/D sequences and finally, their assessment. The A/D simulation begins with an automatic generation of the product from its CAD models, i.e. creation of an assembly graph. The A/D sequence generation is carried out by inverting disassembly sequences automatically produced from the assembly graph while taking into account relative mobilities of components. However, such simulations are generally achieved without considering possible deformations of the moved parts, without evaluating forces required for A/D tasks, etc. The evaluation of the produced sequences either ends the A/D sequencing process or is combined with the sequence generation process. The A/D sequence assessment is based on different criteria: kinematics (component's mobility, assembly directions), geometric (accessibility, A/D path planning), technological (nature of contacts between parts, use of specific assembly tools, standard components), etc. To this end, it can be mentioned that one of the common problems of all automatic approaches for A/D sequencing is the combinatorial problem taking into account a very high number of parts [1, 5, 6]. Moreover, some changes suggested by the A/D software system can be only partially addressed because a qualitative point of view of an expert is often required to define real changes needed in product architecture or the corresponding A/D process. In addition, current automatic DFA systems allow the simulation/evaluation of A/D operations of parts representing rigid objects only. This could create different problems during the effective assembly of deformable parts like springs, deformable plates, pipes or cables, deformable fixations, components linked to bearings or welded parts, problems like unpredictable changes of the A/D process produced that increase the manufacturing time/cost.

Generally, existing DFA approaches include automation aspects of the product design that can explain the development of automatic software tools for assistance and decision-making. This looks interesting for companies because automatic A/D simulation could lead to a reduction of product development time. But does a full automation of the design process present an efficient solution to take into account the diversity of A/D operations and components that must be studied? No, as pointed out at section 4.

3 Semi-automatic DFA methods

Semi-automatic methods for A/D simulation are generally based on the same concepts/criteria of simulation/evaluation/sequencing than automatic methods. The main difference between these DFA categories is the possibility of user's interactions during an A/D simulation, an A/D task evaluation or sequencing process in the case of semi-automatic tools. As an example, the phase of product modeling corresponding to the generation of an assembly graph can be partially carried out by the designer. This allows him/her to describe particular relationships between components: definition of specific assembly surfaces or desired A/D directions, description of specific relationships between welded or deformable parts, etc. The evaluation phase of the A/D process is also based on different geometric, technological, ergonomic criteria, which can be coupled with expert systems or databases [1]. The interactive behavior of semi-automatic DFA approaches avoids some problems of automatic ones like lengthy computing time or interruption of the A/D simulation when the software is not able to produce any result, etc. For example, the difficulty in A/D process evaluation is usually caused by the necessity to take into account simultaneously different or even contradictory design constraints and DFX rules. This problem justifies the use of designer's skills and his/her global vision of the problem complexity to really describe useful constraints and choose qualitatively the best solution.

Thus, the necessity to use various skills during the A/D simulation/evaluation represents the first step towards the development of interactive methods for design and qualitative analysis of product properties related to its manufacturability, assemblability, ergonomics constraints, etc. However, the use of semi-automatic DFA tools do not allow studying complex mechanical systems, i.e. systems containing flexible parts producing large changes of their shapes during their A/D, do not provide an efficient solution when considering the diversity of possible A/D manipulations for a given component, do not take into account human factors during the A/D process, etc. Moreover, the A/D process simulation remains hidden during the computation process and simulation results only are provided [1]. Thus, it is always difficult to monitor parameters during the simulation process that are related to the assessment either of an A/D operation or of the product.

4 Interactive A/D simulation methods

The real-time simulation tools developed in the field of design and A/D assessment can be considered as an extension of traditional CAD tools. In fact, all these systems (CAD tools, robotics software and VR systems) are characterized by a high level of interactivity and a fast display of computation results during the simulation process, the possibility of observing a global layout of different parts of a product, etc. For example, some interactive A/D simulation software tools integrate an A/D sequencing module and allow visualizing the displacements of rigid parts moved in accordance with sequences generated during an A/D simulation [11]. However, a simple visualization of a part or a mechanism does not give access to other parameters helping to assess and optimize the product. Particularly, in the field of A/D and maintenance, the A/D path planning, the accessibility evaluation, the deformation of flexible parts during their A/D, the evaluation and perception of forces necessary for A/D manipulation of a given part are as important as the assemblability evaluation or A/D sequencing [8, 9]. The enumerated parameters help designers assess quantitatively/ qualitatively not only an A/D or maintenance process but also to improve the product structure and can be obtained in real-time using VR systems. The use of VR is generally based on the following aspects:

- Real-time visualization of the computation process with the possibility to immerse the designer into a virtual world represented by a given mechanism [8, 12, 13]. Figure 1a shows an example of Digital Mock-Up (DMU) of a car subsystem. Such a representation enables the assessment of the relative position of different parts of a complex system that is critical for embodiment design, A/D and accessibility evaluation, etc. and eases decision-making during the design review process;
- Real-time A/D manipulation of a given virtual part as well as collision-free path planning. Some VR systems allow to detect/highlight various useful elements helping understand and speed up the A/D simulation: planar or cylindrical surfaces, preferred assembly directions, etc. (Figure 1b) [10]. Moreover, a virtual A/D system can include an A/D sequence generation module [11];
- Process plan of virtual workshops that contributes to automate the manufacturing process simulation (Figure 1c) [14]. Here, virtual modular machines can be dragged and placed

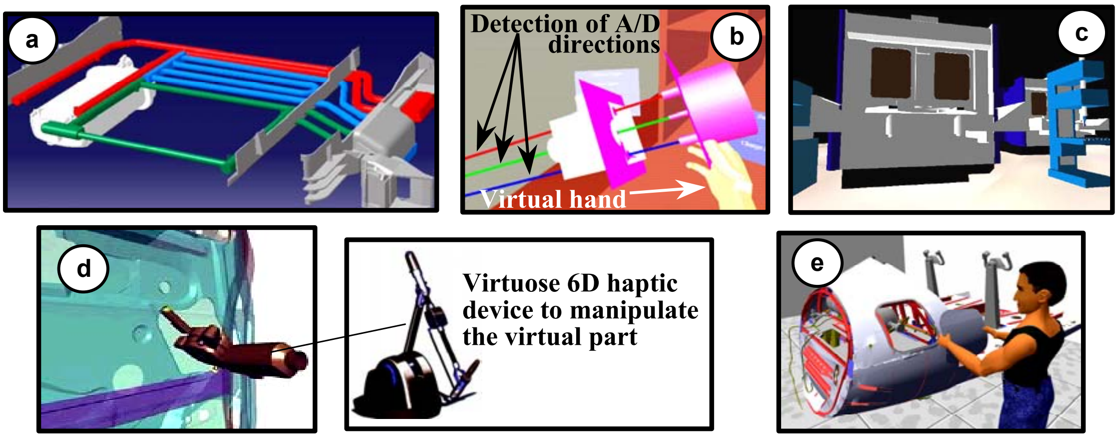

Figure 1. Examples of application of the VR simulation method to A/D, maintenance, design problems: (a) virtual car cooling system (courtesy BMW); (b) real-time A/D manipulation of a rigid virtual part [10], (c) machine cell of a virtual plant [14], (d) virtual A/D operation of a car door by using a VR force feedback (courtesy Renault and Haption), (e) virtual maintenance/ergonomics studies [8].

in the workshop designed to study issues such as plant layout, clusters, component flow analysis, etc. Virtual workshops can be created using different description levels: global (machinery, robot, transportation machines) and/or local (simulation of virtual operator's or component movements) descriptions;

- Physical interaction of an operator with the manipulated part using special haptic hardware (Figure 1d). Such a device allows organizing a force feedback control to "feel" physically virtual parts: their stiffness and weight, friction/inertia forces during the manipulation of the part, contact force in the case of collision between the part and an obstacle, etc.

Generally, VR simulations (A/D manipulation, design review, maintainability study) are based on:

- A geometric representation of the virtual object to be manipulated as well as its external environment describing a product or some subassembly at a given design stage or even a natural environment having aggressive properties;
- A VR device used in order to define input data for a given virtual simulation, e.g. displacements of the virtual part to be assembled, and to perceive simulation results, e.g. the visualization of the moved part and its environment, the perception of feedback forces generated during the virtual manipulation, etc.;
- A VR simulation system computing a virtual event in real-time as well as monitoring the virtual manipulation, e.g. software modules such as collision detection, computation of part deformations, evaluation of contact forces, etc.

Current VR simulation systems often incorporate a module allowing creating virtual models in order to represent the geometry of a part as well as its environment under appropriate format (usually in the VRML format). In industrial practice however, CAD models of the product are used. In fact, the use of already existing CAD models speeds up the A/D process evaluation and hence, reduces the product development time. Indeed, the detailed description of the CAD model is not necessary like with automatic DFA methods. Simplified and/or partial geometric representations of the product or even of some subassemblies at the embodiment or detail design stages can be sufficient. Nevertheless, each CAD model must be transformed into a DMU under a format compatible with virtual simulations [15].

Some CAD systems like Catia of Dassault Systems contain special modules supporting virtual simulations: the designer can perform a virtual manipulation directly in the CAD system as it is shown on Figure 1d. Such a property is very interesting for design because this allows modifying rapidly the geometry of the product directly in the CAD system if necessary (design errors, accessibility or assemblability problems). However, a preparation stage of the CAD model is mandatory after each CAD model modification, i.e. this model must be represented as a set of facets because such a geometric description is required for efficient display of virtual scenes, collision detection, etc.

The global vision of a human being, i.e. the visual overview of a virtual scene, is used efficiently during different assessments through a VR environment (A/D, design review, ergonomics). It can be an immersive 3D representation of a product, the positioning of components of various natures (rigid or deformable parts) in a complex system or the real-time choice of an optimal location of an operator (Figure 1). Such a visual analysis allows designers to study qualitatively the product assemblability, to identify potential design problems at the early stages of the development process.

A VR system acts also as an analysis tool to optimize operator’s actions during the A/D, maintenance task studies by incorporating human factors. In order to perform an A/D task, it is possible to use a virtual manikin based on anthropometrical databases to detect the possible collisions between the user’s body and the external environment (Figure 1e) [8] or to manipulate an object by using optical VR tracking systems [16]. In all cases, the A/D simulation results are visualized in real-time and several designers can observe, monitor, and assess the output information in fast, qualitative/quantitative and collaborative ways. For example, if a new position of one of the pipes of a car subsystem is better from embodiment design or assembly points of view but not taking into account maintenance or ergonomics constraints (Figure 1a), this problem can be handled immediately because the corresponding designers are present. Hence, such an assistance analysis during the product development eases decision-making in the case of study/optimization of complex mechanical systems.

The interactive simulation methods allow performing detailed studies of a product from different design points of view and can assist the automatic assessment of A/D process based on current DFA methods. A given A/D sequence, initially produced by an automatic A/D system or provided by a designer, can be inserted in a VR environment and the process simulation can be displayed in real-time. Hence, the A/D process is not hidden anymore, and virtual manipulation is quickly evaluated by the designers in collaborative way using various criteria like planning collision-free A/D path having a minimal length, A/D manipulation requiring the development of minimal forces, reduction of the A/D task time, etc. [16]. Therefore, the real-time analysis/evaluation of a product and its A/D process in a VR environment can be achieved:

- Quantitatively: through the application/perception of forces during a virtual A/D, monitoring and perception of collisions with obstacles, detection of preferred A/D directions, computation of virtual part deformation, real-time evaluation of various parameters required for A/D analysis (stress in the manipulated part, maximal forces that can be applied to the part during the A/D manipulation), etc.;
- Qualitatively: using the direct manipulation of a component, visual control of virtual events, avoidance of obstacles during the A/D path planning, generation of clear information about the deformation of flexible parts to evaluate their assemblability or accessibility, A/D nature (manual, robotized) or appropriate A/D tool choice, etc.

5 Use of VR for evaluating A/D tasks of complex systems

5.1 Physically based virtual simulation of complex mechanical systems

As it has been mentioned above, the virtual A/D simulation allows the designer to determine or study A/D sequences and paths, to evaluate/optimize the A/D process of complex systems containing deformable parts, components having complex shapes or incorporating a physical behavior, etc. Potentially deformable components (springs, plate/shell type parts, fastening rings) or flexible parts (hoses, durits, cables) subjected to large shape changes form a specific category of components frequently met in industrial practice (Figure 2). These parts are characterized by specific mechanical behaviors (small/large displacements and/or deformations) and require particular software modules to describe adequately their A/D process with regard to rigid parts commonly handled by automatic A/D simulation systems. Also, they significantly increase the combinatorial complexity of the A/D operations.

Taking into account the mechanical behaviour of such parts is critical for adequate analysis of the A/D process. For example, it is important to produce a physically realistic shape of the virtual deformed part because it allows to check the lack of real interferences between the part and its environment during the A/D path planning, to check the assemblability as well as the relative position of the parts, which will be connected to the flexible component manipulated. The realistic forces associated with a flexible part deformation process and produced in real-time by a virtual system are also very useful to assess the A/D operation. For example, it allows a designer to improve an A/D operation by searching an A/D path corresponding to minimal forces applied to the part to reach a given configuration. Adequate internal forces of flexible parts give access to an accurate stress state evaluation in the deformed part during its A/D manipulation. Such an evaluation makes it possible to assess a final stress state in the flexible part that can be critical if large values of external forces must be developed and the assembled part is significantly deformed to achieve the assembly goal. According to the component structure, an overstressed state in the deformed part produced by inadequate operator’s actions during the assembly process, can negatively act on the targeted exploitation of the product.

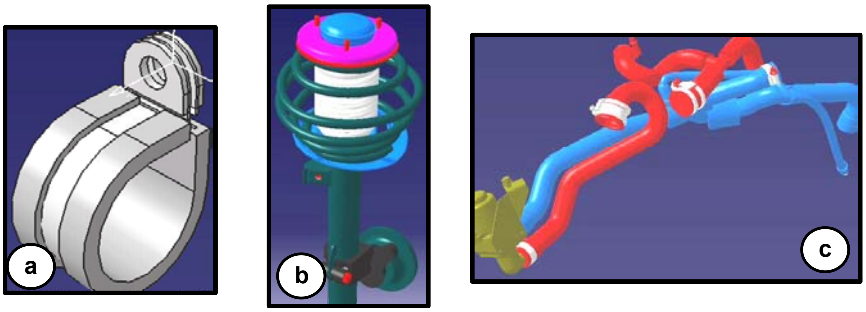

Figure 2. Examples of deformable parts used in A/D context (courtesy BMW):
(a) deformable fixing part; (b) spring; (c) flexible hose system.

Indeed, such useful data can be obtained if the virtual deformable part is correctly modeled during the A/D manipulation. Despite of the advantages of virtual A/D, immersive display and force feedback interfaces do not provide the user all information about the complex behavior of flexible parts during their manipulation. In fact, most of the current CAD and VR systems for A/D are based on a rigid representation of objects and do not handle adequate and fast simulations of flexible part behaviors characterized by complex relationships between the deformation of the part and the forces/moments applied [16].

The mechanical behavior of flexible parts (e.g. presented on Figure 2c) during a virtual A/D can be taken into account by incorporating accurate mechanical models into a VR simulation system. Such models allow considering simultaneously variations of forces/moments in intensity and/or direction (linear or non-linear forces to be applied to a virtual part), large displacements in terms of geometric boundary conditions (final assembly position, A/D path) characterizing non-linear geometric changes of the shape, complex behavior laws of the flexible part material, etc. However, mechanical models are subjected to a real-time simulation constraint as well as a compatibility with the current VR devices, i.e. the nature of input/output data of the models used and VR devices must be the same in order to perform real-time and qualitative analysis of a virtual A/D task.

5.2 Example of evaluation a virtual assembly operation of a flexible part

In order to illustrate an interest of virtual A/D of parts having a complex behavior, we propose to study in this section an assembly operation of a flexible beam type part. This category of complex parts aggregate components such as harnesses, hoses, cables and hence, represents a frequent class of flexible parts usually met in the A/D context.

A typical A/D operation with a flexible beam part can be reduced to the following scenario. When one extremity of a flexible part is free and the operator wishes to insert this extremity or to get access to another component hidden by this flexible part, the operator bends the flexible part by loading its free end. Then, under the corresponding external forces the flexible part produces large shape changes called “large displacements”. The large displacements generate non-linear force Boundary Conditions (BCs), i.e. force locations move during the deformation process. Complex relationships between the deformation of the flexible part and the forces/moments applied have a non-linear nature [16].

First of all, physical experiments representing an A/D operation of a flexible part have been performed. These experiments consist in a real assembly manipulation of a flexible beam part and represent a particular interest for virtual A/D. Indeed, current VR input devices are mainly restricted to the definition of geometric BCs, i.e. a set of positions and/or orientations of the manipulated virtual part is prescribed directly by the operator, measured by a VR input device and represents geometric input data for mechanical modeling during a virtual A/D simulation. The aim of this experiment is to provide reference geometric data representing a prescribed A/D path to evaluate the adequacy of the mechanical model of a given flexible part during their A/D that will be simulated numerically. This experiment contributes to the validation of the proposed approach.

Let us consider the simulation of a typical A/D operation: one extremity of a flexible plastic pipe is mounted, and the operator wishes to fix its free extremity by inserting this free end in a hole (Figure 3). In this case, the free extremity of the pipe follows a user-prescribed assembly path. An optical VR motion analysis system Optotrak has been used to record key point positions characterizing the set of deformed shapes and the assembly path of the flexible pipe in 3D and in real-time. This measurements use infrared diodes attached to the manipulated pipe. The recorded data represent geometric input BCs for a virtual simulation of the same assembly task: $\mathbf{X}$ – assembly path (vector of key point coordinates) and $\mathbf{\Theta}$ – variable angle law approximated from the 3D deformed shapes of the flexible pipe (vector of angles determining the current orientation of the manipulated free extremity of the flexible part).

Then, the same assembly operation has been numerically modeled using a non-linear mechanical model of flexible beams describing accurately a complex behavior of flexible beam parts subjected to large displacements and non-linear BCs [16, 17]. This mechanical model is based on non-linear relationships between geometric parameters describing a 3D shape of the deformed flexible part (positions, orientations, curvatures) as well as internal forces/moments in the part expressing an equilibrium configuration of the deformed part. This model has been incorporated into a software system allowing modeling quickly and accurately the deformation of a flexible beam part subjected to BCs of various natures in accordance with input parameters required by the mechanical model as well as input/output VR devices. The numerical simulation results will help correlate the deformed shapes computed with those measured, and force parameters can be evaluated to analyze the corresponding assembly task.

Current VR devices and particularly optical tracking systems are usually restricted to geometric BC specification and cannot provide the information about realistic forces developed during both real and virtual A/D operations of flexible parts. Thus, a next step is the numeric evaluation of realistic forces that must be developed by the operator during a given A/D task and applied to the flexible part to reach a prescribed A/D path produced in real-time. The 3D deformation simulation of a given flexible pipe behavior is based on the mechanical model of flexible beams incorporated and requires the following input data:

- BCs, e.g. description of fixed extremity of the flexible pipe as well as geometric data (assembly path) recorded during the real manipulation of this part. Generally, the A/D paths are produced by the operator, measured by a VR device and directly transmitted to a VR simulation system;
- "Behavior" input data, which group all parameters defining a mechanical behavior of the deformable part: material characteristics, initial stress state in the part, etc.;
- Geometry of the part: its length, cross-section description, initial shape of the part.

The output data produced by the mechanical model are deformed shapes of the flexible pipe, conforming to the measurements, and realistic force/moment variation laws. These laws are the mechanical answers of the deformed system, i.e. follower forces Q_j and moments M_j, $j=\{1,2,3\}$, which must be applied to the free extremity of the flexible pipe to obtain the user-defined assembly path: Q_1 is the axial force, Q_2 and Q_3 are the bending forces, M_1 is the torsional moment, M_2 and M_3 are the bending moments. These force parameters can help analyze an A/D operation.

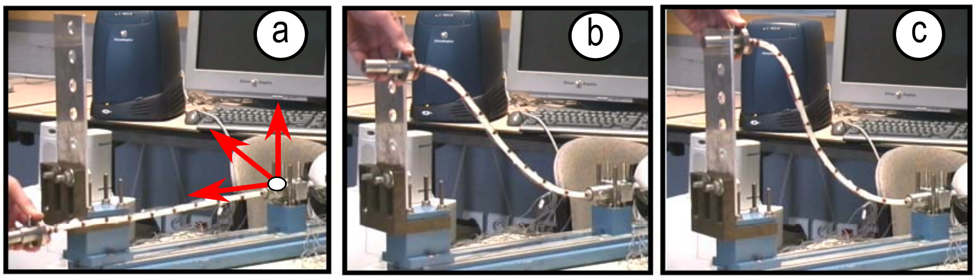

Figure 3. Experimental sequences of flexible pipe assembly operation:
(a) initial shape; (b) one of the intermediate deformed shapes; (c) final assembly configuration.

Figure 4a depicts the results of the deformed shape generation of the flexible pipe following an assembly path prescribed by the operator at key points i. Figure 4b shows the numerical results of follower forces $Q_j(i)$ and moments $M_j(i)$ that must be applied to the free extremity of the pipe and points out that the follower axial force Q_1 and bending moments M_2 and M_3 have a significant influence on the 3D deformation during this assembly operation. This is correlated with the real manipulation of the part (influence of compression force and bending moments/forces).

Some important aspects have been observed during the experimental study to validate qualitatively the simulation. Firstly, different zones of force/moment variation laws presented on Figure 4b can be distinguished [16]: manipulation, approach and insertion zones. The manipulation zone corresponds to the “stroll” of the human hand (Figure 4a). This assembly stage is characterized by very large displacements, large shape changes and variations of force/moment values. In the approach zone, the operator approaches towards an assembly goal – the hole. So, this assembly stage is characterized by small changes of the pipe shape and of the associated force/moment values before starting the flexible pipe extremity insertion in the hole. Finally, the last assembly zone corresponds to the effective insertion of a rigid component attached to the flexible pipe in the hole. The last assembly stage is characterized by small displacements along the x axis only without large changes of pipe shape. Thus, there are no significant changes on the level of forces/moments really developed and produced by the mechanical model.

Abrupt changes (peaks) along the force laws characterize an obstacle (metallic plate) avoidance (Figures 3b, 4b). This corresponds to movements of the operator’s hand, i.e. the compression and bending force/moment application to avoid the collision, and represents one of optimization task associated with the A/D path planning process. Indeed, it is preferable to avoid such peaks because it increases the forces/moments developed by the operator.

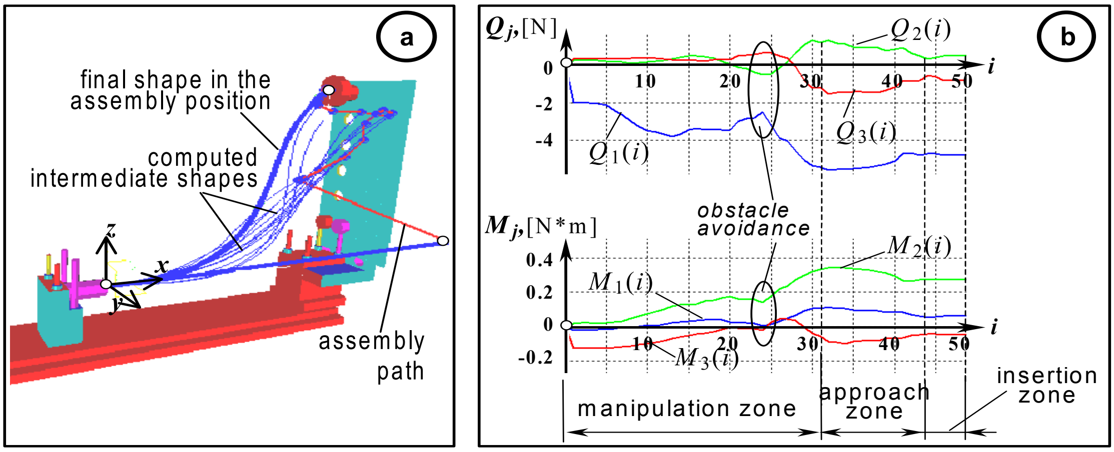

Figure 4. Output data produced by the mechanical model of flexible beams:
(a) evaluation of realistic deformed shapes; (b) realistic follower forces must that be developed by the operator.

The realistic deformed shapes of the flexible pipe can be used in accurate collision monitoring: realistic shapes generated by the mechanical model allow computing realistic interferences with external environment during the collision-free A/D path planning. The realistic values of the required forces/moments can be used in ergonomics assessment of a given A/D task as well as to choose a type of A/D operation (manual or robotized, how many human hands are required?), etc. In the present study, the force values Q_j varies between -6 and 2 N and the moment values M_j span -0,2 and 0,4 N·m. Hence, this assembly operation is valid from an ergonomics point of view and is conform to the real operation accomplished.

The realistic deformed shape of the virtual flexible part allows assessing other parameters for a given A/D task. For example, geometric torsion and curvature of the part, which represents technological constraints) can be easily computed from the deformed shape and assessed during the virtual A/D process in real-time. Furthermore, the realistic internal forces in the deformed flexible part give access to adequate assessment of a stress state in the part during the A/D task. This parameter represents a mechanical design constraint and is very useful to evaluate the stress state in the assembled part that is critical for a normal exploitation of a given mechanical system. This parameter is hardly addressed by current automatic A/D simulation methods.

6 Comparative study of automatic DFA and interactive VR methods

Different aspects related to the simulation and evaluation of virtual A/D complex mechanical systems have been illustrated and discussed above. In this section, we identify and compare key elements of (semi-) automatic DFA and interactive VR methods used for simulation of A/D or maintenance operations. Such a comparative study will help demonstrate in general what is the impact of VR simulation tools on DFA and product development processes.

The key elements of existing A/D simulation methods considered in our work are:

- Aims of A/D simulation and analysis of simulation results;
- Type of component that can be studied;
- Product development stage at which the A/D simulation can be performed;
- Level of geometric description of the product for A/D simulation;
- Nature of product components that can be used for the A/D simulation;
- A/D simulation time.

These aspects are clustered and briefly presented in Table 1. A comparative analysis of these elements is given below.

Table 1. Comparison of key elements characterizing various A/D simulation methods.

Key elements of A/D simulation methods	**Automatic and semi-automatic DFA methods**	**Interactive VR methods**
Aims of A/D simulation	A/D sequencing, quantitative and general evaluation of A/D process	Detailed, quantitative, qualitative studies of a given A/D or maintenance task
Type of product that can be studied	Essentially new product	New or existing product
Product development stage	Detailed design, re-design	Embodiment or detailed design, re-design
Description of the product for A/D simulation	Detailed description of the final product, CAD data without geometric modeling errors	Detailed/simplified description of the external environment under an adequate format
Nature of product components	Rigid parts only	Rigid and deformable parts
Simulation time	Computation time is not a constraint	Computation time is a significant constraint

Aims of A/D task simulation:

The aims of an A/D task simulation based on (semi-) automatic DFA methods is to assess globally the assemblability of a product, to generate A/D sequences, to evaluate automatically an A/D process by choosing the optimal assembly sequence by using various criteria [1, 2, 5]. Thus, a product is quantitatively studied. The designer may interrupt the simulation process if a software is unable to produce a sequence or if a proposed solution seems not acceptable. However, it is difficult to set up criteria for maintenance tasks involving a part change and hence, requiring either one specific A/D task or several A/D operations usually different from the dismounting order automatically established from general rules of DFA/DFMA (Design For Manufacturing and Assembly) methods. Generally, the analysis process of A/D simulation results is performed at the end of the computation process.

Virtual A/D simulation assists the evaluation/optimization of A/D sequences previously established, e.g. using an automatic method, to perform a complementary and detailed analysis of a given A/D task. Here, the functions of VR like direct manipulation, visual or force feedback control of an A/D process, multi-criteria evaluation of A/D based on the global vision of the designers are efficient [8, 9, 11]. Such a quantitative/qualitative analysis allows a designer to understand in real-time complex phenomena taking place during an A/D operation, e.g. deformation of flexible parts. Thus, the A/D simulation process is not hidden anymore but eases the assessment/optimization of the product. Also, VR simulation methods help train the staff members (e.g. maintenance operators) to optimally achieve a given A/D task. Compared to automatic A/D simulation methods based on the traditional DFA approaches, the analysis of results produced by VR simulation system is generally achieved directly, during the virtual A/D modeling.

Type of product that can be studied:

Automatic DFA methods are generally used for studying of a new product during design. Such a study is carried out from the point of view of DFA/DFMA principles as well as specific criteria set up by a designer [1, 2]. A new A/D process is described by a general sequence at the end of the design (or re-design if necessary) process.

In the case of virtual A/D or maintenance simulation, the analysis of these tasks may address:

- A new product: an A/D analysis is achieved in a local but more detail way with regard to automatic methods;
- An already existing product: an A/D analysis for a given maintenance task when the use of automatic methods is not appropriate any more [8, 11]. Indeed, general rules of automatic A/D evaluation are not directly applicable to a specific maintenance task requiring an assessment of the accessibility to a part, free-collision A/D path planning in hardly accessible as well as invisible zones, avoidance of damage to the flexible part manipulated or other components, etc. Virtual A/D allows considering these problems.

Product development stage at which the A/D simulation can be performed:

Automatic DFA methods are in general used during the detailed phase of design. Indeed, the assemblability studies, the automatic generation of A/D sequences and their (semi-) automatic evaluation, the choice of production equipments, etc. require a detailed description of the final product or its subassemblies. This requires the creation of CAD models in order to establish a graph of product decomposition for assembly sequencing, for example. According to A/D analysis aims and simulation result, a re-design of the product involving major geometry or A/D sequence modifications may be necessary.

Virtual A/D simulations can be performed either at the embodiment or detailed design stages [16]. Indeed, an A/D operation analysis of a given component does not require a detailed geometric representation of a product. A virtual A/D simulation can be carried out from a partial representation of the product and its external environment. Thus, possible modifications of a product or its A/D process have a “local” character if a re-design is required.

Levels of geometric description of the product for A/D simulation:

As mentioned above, (semi-) automatic A/D simulation methods require a detailed geometric description of a final product [1]. This means that a CAD model of the product should be free of geometric modeling errors like surface connection problems, superposition/intersection of surfaces, open volumes, badly oriented surfaces, etc. In fact, a CAD model containing such errors does not enable to determine correctly the mobilities of components.

In the case of virtual A/D simulation, a detailed or simplified (or even approximate) geometric description of the product can be used [15]. Indeed, it is generally necessary to model an external environment of a given virtual part. Currently, this environment is “static”, i.e. without geometric changes during the virtual simulation. However, each model of external environment, e.g. a CAD model of a mechanism where a given part will be mounted, is subjected to specific description constraints required by a VR simulation system. Thus, a preparative phase of representation of all geometric models, external to a VR environment, is necessary to describe the transferred models in a specific format, e.g. VRML format. Anyhow, it is necessary to distinguish the model of the virtual part manipulated from its external environment.

Nature of product components:

The simulation of an A/D process based on automatic DFA methods can be generally performed for rigid components only [1, 5, 6]. If a given mechanical system contains deformable parts, these ones will be represented as rigid, which is not always adequate with regard to real assembly processes, e.g. bearings or springs, flexible pipes, axes, harnesses, etc.

As illustrated above, it is possible to simulate more precisely the virtual A/D tasks of components subjected to large shape changes by incorporating accurate model of such parts into a VR environment. It is also possible to associate some physical properties to the manipulated part (weight, stiffness) and thus, to perceive them during the A/D manipulation [10, 11]. This is very important not only for adequate assessment of assemblability or maintainability of a product containing flexible parts but also for the design of such complex mechanical systems. For example, physical prototypes are often required to allow the designers to determine manually the part lengths, A/D paths, positions of fasteners in the case of design of flexible pipes, cables harnesses, etc. Moreover, the design of such systems is usually complicated by accessibility and visibility problems, the necessity of changing frequently the worker’s position during the routing process, anthropometric particularities of each human being, etc. Virtual simulation allows the designers to generate and to study various alternative solutions, ease decision-making based on collaborative assessment of the mechanical system. Consequently, all necessary design modifications, e.g. the geometry or the material of the manipulated virtual part, local geometric changes of external environment as tests of fastening means or connections between the part and its environment, new positions/orientations of fixations, new A/D sequence involving the modification of environment geometry, etc., can be promptly performed, because the designers exploit a geometric model of the virtual DMU based on the corresponding CAD model.

Computation time during an A/D simulation:

A short computation time of the A/D simulation process is required. Nevertheless, the simulation time represents the main constraint for any virtual simulation compared to automatic methods. All models incorporating a VR environment are subjected to real-time simulation constraints: generation of virtual part movements, lack of interferences between the manipulated part and its environment, generation of a flexible part deformation, etc.

7 Conclusion

The advantages and lacks of current A/D simulation methods have been presented in this paper. Particularly, different problems met during the A/D, maintenance, and design studies of complex mechanical system like mechanisms containing deformable parts have been discussed. To this end, the interest of the use of VR approach in assemblability assessment of such systems has been demonstrated, and a comparative study of DFA and virtual A/D simulation methods has been achieved to show the potential of VR approaches.

As shown, automatic DFA/DFMA methods are mainly used for a general improvement of a product taking into account various criteria. Consequently, the suggestions generated by such tools can involve a significant re-design of the product or its A/D process. Because the computation process of automatic methods is hidden, a quantitative analysis is possible at the end of A/D simulation process only. This does not allow evaluating qualitatively the assemblability of complex mechanical systems and incorporating the diversity of A/D tasks. Therefore, automatic simulation systems based on traditional DFA methods are more suited to the last phases of the design process only.

A possible solution is the development of new analysis tools incorporating various phases of the design process in order to perform qualitatively the product evaluation from the mechanical design, A/D, manufacturing, maintenance, ergonomics, recycling, etc. points of view early in the design process. The method discussed in the present paper is based on a real-time A/D analysis using VR techniques. The evaluation of A/D tasks in a VR environment is more local regarding automatic DFA methods and allows taking into account other criteria that are hard to incorporate into automatic approaches, e.g. direct manipulation, real-time perception and analysis of simulation results during the computation process, quantitative/ qualitative evaluation of particular A/D tasks, consideration of possible part deformation during the A/D process, etc. Virtual simulations can be accomplished at the embodiment or detailed design stages as well as during the analysis of specific A/D or maintenance tasks of the existing product. Designers can perform qualitative analysis during the A/D simulation in collaborative manner based on their global vision and necessary modifications can be performed promptly.

Thus, the use of VR tools can have a significant impact on the development of DFA methods. These new analysis tools can be used at different stages of the product development, allow to model/analyze a given product quickly and objectively through different design constraint points of view, to assist/ease the optimization of complex systems by providing useful parameters for their multi-criteria assessment. The real-time result analysis through the virtual A/D speeds up the modifications of the product during the simulation process and not waiting the end of every simulation. Consequently, this reduces the number of iterations during the product development and so, decreases the cost and the time of the product development cycle. Hence, VR tools give design activities an additional dimension through their common use with traditional DFA/DFMA methods.

References

[1] Rejneri N., Léon J.-C., Débarbouillé G., "Early Assembly/Disassembly simulation during a design process", Proceedings of the Conference ASME DETC'01 Design For Manufacturing, Eds. ASME, Pittsburgh, USA, 2001.

[2] Boothroyd G., Alting L., "Design for assembly and disassembly", Annals of the CIRP, Volume 41/2/, 1992.

[3] Allenby B.R., Richards D.J., "The Greening of Industrial Ecosystems", Eds. National Academy Press, Washington, USA, 1994.

[4] Blanchard B.S., Verma D., Peterson E.L., "Maintainability: A Key to Effective Serviceability and Maintenance Management", Eds. John Wiley & Sons, Inc., 1995.

[5] Laperriere L., "GAPP: Generative Assembly Process Planner", Journal of Manufacturing systems, Volume 15(4), 1996, pp. 282-293.

[6] O'Shea B., Grewal S.S., Kaebernick H., "State of the art literature survey on disassembly planning", Journal Concurrent Engineering: Research and Application, Volume 6(4), 1998, pp.345-357.

[7] Hergenröther E., Knöpfle C., "Cable Installation in Virtual Environments", Proceedings of the IASTED Conference on Modeling and Simulation, Anaheim, USA, 2001, pp. 276-280.

[8] Chedmail P., Le Roy C., "A Distributed Approach For Accessibility And Maintainability Check With A Manikin", Proceedings of the Conference ASME DETC'99 Design Automation Conference, Eds. ASME, Las Vegas, USA, 1999.

[9] Gomes de Sa A., Zachmann G., "Integrating Virtual Reality for Virtual Prototyping", Proceedings of the Conference ASME DETC'98 Design Automation Conference, Eds. ASME, Atlanta, USA, 1998.

[10] Jayaram S., Wang Y., Jayaram U., Lyons K., Hart P., "A Virtual Assembly Design Environment", IEEE Journal of Computer Graphics and Applications, Eds. IEEE, Volume 19(6), 1999.

[11] Carrillo A.R., Beloki O., Casado S., Gutierrez T., Barbero J.I., "Virtual assembly and disassembly simulation on a distributed environment", Proceedings of the Conference Virtual Concept 2003, Biarritz, France, 2003, pp. 50-55.

[12] Mahoney D.P., "Driving VR", Journal Computer Graphics World, Volume 18(5), 1995, pp. 22-31.

[13] Owen J.V., "Making Virtual Manufacturing Real", Journal Manufacturing Engineering, Volume 113(5), 1994, pp. 33-37.

[14] Kesavadas T., Lefort L., Ernzer M., “Interactive Virtual Factory for Shop Floor Design using Cellular Manufacturing Concepts”, State University of New York, http://www.vrlab.buffalo.edu/project_vfact/vsmm99.htm, New York, USA, 1999.

[15] Drieux G., Léon J.-C., Guillaume F., Chevassus N., “Tools and criteria for data transfer CAD to VR environments”, Proceedings of the Conference Virtual Concept 2003, Biarritz, France, 2003, pp. 296-303.

[16] Mikchevitch A., Léon J.-C., Gouskov A., “Proposal of Criteria Characterizing Assembly Operations of Flexible Beam Parts for VR Applications”, Proceedings of the Conference ASME DETC’04 Design For Manufacturing, Eds. ASME, Salt Lake City, USA, 2004.

[17] Svetlitsky V.A., “Statics of Rods”, Eds. Springer, Germany, 2000.

Corresponding author: Pr. Jean-Claude Léon
National Polytechnic Institute of Grenoble
Soils, Solids, Structures (3S) Laboratory
BP 53X, 38041 Grenoble
France
Phone: (33) 4 76 82 51 27
Fax: (33) 4 76 82 70 43
E-mail: Jean-Claude.Leon@inpg.fr