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A simulation environment for assembly operations involving flexible parts

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Abstract – Virtual reality simulations of maintenance operations are a key simulation to improve the performance and quality of products. Real-time requirements of virtual reality systems face difficulties when coping with flexible components exhibiting strong non-linear behaviour. To this end, an interactive system incorporating mechanical models of flexible parts behaviour is described in the present paper. The approach proposed will be used as a basis to the simulation of flexible parts in a virtual reality environment for the evaluation of assembly operations. First of all, the study of current assembly planning systems based on the real-time approaches is performed. Secondly, a new system integrating real-time and interactive mechanical simulation approaches is proposed. An adequate simulation of the flexible components to estimate the assemblability in a virtual reality is discussed. This is especially true when flexible parts are subjected to large displacements. Finally, the example of the interactive mechanical behaviour model used into an assembly context for the virtual reality simulation environments is represented.

Key words: Assembly / flexible parts / large displacements / mechanical behaviour / virtual reality

Résumé – Un environnement de simulation des opérations d'assemblage de composants flexibles. La simulation d'opérations de maintenance en réalité virtuelle est un aspect important pour pouvoir améliorer la performance et la qualité des produits. Les systèmes actuels de réalité virtuelle causent des problèmes lors de la simulation du comportement non linéaire de composants flexibles. De ce fait, un système interactif incluant des modèles mécaniques de composants flexibles est présenté. L'approche proposée sera utilisée en tant que base pour la simulation de pièces flexibles dans un environnement de réalité virtuelle lors de l'évaluation des opérations d'assemblage. Dans un premier temps, l'étude de systèmes actuels de planification d'assemblage est effectuée. Dans un deuxième temps, un nouveau système intégrant des aspects mécaniques de simulation en temps réel et interactifs est proposé. La simulation adéquate de composants flexibles afin d'estimer l'assemblabilité dans l'environnement de réalité virtuelle est discutée. Ceci est particulièrement important quand les pièces flexibles sont soumises aux grands déplacements. Finalement, un exemple du modèle de comportement mécanique interactif utilisé dans un contexte de planification d'assemblage pour la simulation dans un environnement de réalité virtuelle est représenté.

Mots clés : Assemblage / pièces flexibles / grands déplacements / comportement mécanique / réalité virtuelle

1 Introduction

The field of A/D (Assembly/Disassembly) fits among the domains which interest the industry when the target is either to incorporate or to optimise the triplet "quality – delay – cost" during the product design process. An A/D simulation process falls into the industrial preoccupations because it reduces the product design cycle as well as the number of necessary physical prototypes, which forms also a source of considerable cost reduction. The A/D aspects express also requirements for the design and the manufacture of "the right" product, i.e. the product which fulfils at best the service functions in terms of reliability, comfort, accessibility, maintenance, etc. Therefore, the simulation of A/D processes should take place as soon as possible during the design of mechanical systems,

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Nomenclature

E	Young's modulus of the material, MPa
$\mathbf{H}$	flexible beam state vector
I	moment of inertia of the beam cross-section, m4
M	bending moment in the beam, Nm
N	longitudinal force in the beam, N
Q	shear force in the beam, N
s	curvilinear abscissa along the beam neutral line, m
x, y	coordinates of a point on the beam neutral line, m
θ	angle rotation of the beam cross-section

this is particularly true for engine bay maintenance in the car industry [1, 2]. Then, it is essential to be able to set up an effective simulation approach of this process where human activity is critical.

Despite of the diversity of VR (Virtual Reality) approaches and devices, the applications concerning the A/D process are rare and essentially restricted to rigid bodies. Such rigid objects are moved into a static VR environment where all obstacle positions are known. The A/D path search process is accomplished from this configuration and the rigid body movements are monitored by standard VR input devices. It is more difficult to model the flexible behaviour of components like harnesses, hoses, etc. during the A/D process simulation [3, 4] because a deformation model is required to simulate the shape changes of such components when they are loaded. It is important to perform an adequate simulation of such flexible parts into a VR environment because in this case, the assembly planning systems need specific simulation functions to estimate the assemblability of flexible components in terms of geometry as well as forces.

Thus, the work presented here aims at taking into account the complexity of the flexible component behaviour to structure assembly planning simulation systems by means of VR environments. The key feature of the current approach is to insert two complementary mechanical models to handle real-time requirements as well as realistic forces in a VR system. Furthermore, the interactive models of the flexible part behaviour proposed are fast enough to consider the combinatorial aspects of the A/D sequence search and the real-time simulation requirements of this process by means of VR environments to help the user identify paths and A/D operations.

2 Problems of current assembly planning systems

The aim of the present work is to develop the assembly planning technology by informing and facilitating both human and robot assemblies of mechanical systems. Current automatic approaches in the A/D field generate assembly processes using the disassembly decomposition of a product into a set of elementary components. Thus, the automatic approaches describe an assembly sequence as the opposite of a disassembly process. Most often, the number of A/D sequences increases exponentially according to the mechanical system complexity. Hence, it is necessary to reduce the amount of sequences of the A/D process with the use of different simulation criteria: tool change number, operations parallelism, operation time, technological data associated to component geometry, accessibility, etc. [5–11].

Generally, the searches for assembly paths are based on models representing rigid parts and real-time techniques in VR environments to immerse a user into a given configuration. Multi-agent approaches ease the generation of valid paths. For rigid objects, complex scenes can be handled with VR systems because the intrinsic shape of the components is not modified during the real-time computation processes. Also, the execution of A/D operations is often difficult because the working space can be reduced or even invisible in reality.

Moreover, the specific behaviour and potentially large displacements of the flexible parts generate complex A/D paths that increase the probability of collisions. Simultaneously, variable forces in intensity and direction become also a part of the simulation process to evaluate the accessibility, the dismountability of a component. This lack of accessibility can cause different problems for the worker holding the part to be assembled: increase of the execution operation time, worker's fatigue, possibility of damaging parts, etc.

At present, the consideration of the flexible component behaviour has been loosely incorporated into the A/D context by means of VR technologies [4, 12, 13]. The use of such technologies is an effective alternative with regard to the current automatic approaches for the A/D operation simulations. In fact, it seems efficient and important to enhance the search sequence strategy concerning a flexible part to be assembled or extracted through the use of the high level input devices and the global vision faculty of the user who will manipulate this part in the VR environment. This environment must perform the search for collision-free paths of the flexible part, evaluate the forces taking place during the operation, between the manipulated component and its environment. Such a real-time analysis can be accomplished using the part shape from the complicated and delicate on-line sequential movements. So, the VR system must be able to provide the designer, during the simulation process, a clear information about the three-dimensional object geometry and the forces/moments to be applied.

In fact, the display technologies involving perspective, shading and animation of geometric models with expensive haptic interfaces, which allow direct object manipulation, do not provide the user the sufficient information about the component of interest. Despite of such interfaces that include anthropomorphic geometry and provide partially realistic force feedback and movements, the computer assembly planning system cannot provide satisfactory solution without the insertion of mechanical models capable of handling large displacements, realistic forces during the simulation process. For example, haptic devices are not necessary capable of producing forces and moments with a magnitude and a direction, which are conform to the real forces and moments required for an A/D operation involving either a rigid or a flexible component. Hence, an important point is an adequate simulation of the flexible parts in a VR environment because current VR approaches lack of deformation models of flexible components both in terms of geometry of deformed objects and of realism of forces required during an A/D operation. Thus, the assembly planning systems need specific simulation functions to estimate the assemblability both from geometric and mechanical point of views. This is especially true when the flexible parts are subjected to large displacements.

Hence, it is necessary to work out an approach including a behaviour model of deformable objects and taking advantage of real-time capabilities of VR systems in terms of geometry representation, input from VR sensors like Polhemus trackers.

3 Formulation of flexible part assembly problems

The designer must be able to move and see the parts manipulated in a VR environment as well as feel them to control the assembly operations. The virtual assembly allows the designer to consider the possible assembly sequences and thus, optimise the assembly process of mechanical systems containing the flexible components. This can be reached if the virtual flexible object is correctly represented. Such a realistic representation requires an adequate simulation of flexible components, which needs a new simulation approach based on new criteria since full real-time simulation of non-linear mechanical behaviour is currently out of scope for VR systems. The assembly planning system must be able to generate a mechanical model producing the realistic estimations of:

- displacements of the flexible part under a given load to produce the deformed shape of the component,
- forces/moments to be applied to obtain prescribed geometric configurations (particular point positions or shapes of flexible parts) using VR sensors input,
- forces between flexible parts and their exterior environment,
- internal forces/moments of a flexible part under a given load.

Thus, the A/D operation simulation system serves as a basis in the evaluation and the design of A/D sequence sets. The part shape is important because it allows the analysis of a path to check the lack of interferences between the manipulated component and its environment. The forces produced by such simulation model will be used to assess the deformation of an object, to contribute either to the determination of equipments or the ways the operation can be executed (one or two human hands, robot arm, pincers, etc.) during the assembly process or to the evaluation of the ergonomy of a task. The organization of the simulation system proposed is based on a trade-off between the accuracy required for realistic simulation of forces and the real-time generation of frames for an immersive display of a VR scene. From the A/D point of view, this has been considered as equivalent to two complementary time scales: a real-time and an interactive ones as described in the next section.

4 Principles of assembly operation simulation environment

This paper proposes an alternative approach based on the integration of particular models in the VR environment and hence, a global reorganisation of a virtual tool for virtual assembly purposes. In fact, it seems efficient to organise differently the general strategy of virtual flexible component manipulation for the search of assembly sequences by taking into account the flexible component behaviour into the virtual assembly. So, important aspects focus on:

- real-time models to mimic the deformation process of flexible components for a reduced range of forces for real-time update of geometry modifications related to input changes of the VR sensors,
- interactive models to depict accurately the behaviour of a flexible component for a large range of forces and boundary conditions to provide realistic forces and get the real-time model coherent in the VR environment thus aiding to select the optimal A/D sequence.

In fact, it is possible to speak about the couple "real-time approaches of assembly planning systems – interactive mechanical behaviour simulation systems" in the VR. A new architecture of proposed VR environment is based on this couple: it incorporates two levels of simulation and finally, assists accurately users in the virtual assembly (Fig. 1). Therefore, real-time and interactive models form two complementary levels to handle deformation models of progressive accuracy.

The A/D simulation of the flexible part begins with the representation of the external virtual environment and the parts already assembled under given conditions. An important point is the assumption that assembled components can be flexible. In this case, it is necessary to specify such deformable components to take into account, if necessary, the flexible behaviour of these components in the case of contact with other components (flexible or rigid). The user can move himself within the scene using various VR devices to observe a part and perform A/D operations. The virtual hand or the robot arm form the device used to grasp and act over flexible parts.

As an example, consider the apparently trivial fixation operation of a hose style flexible object into a hole. The position of this hole can be represented by point coordinates and the model of this deformable part is assigned by the operator. This deformable hose is then moved to its fixation position at one end. In this case, it is necessary to calculate the realistic shape of the flexible hose and the adequate forces/moments to be applied to reach the target position represented by coordinates of the hole.

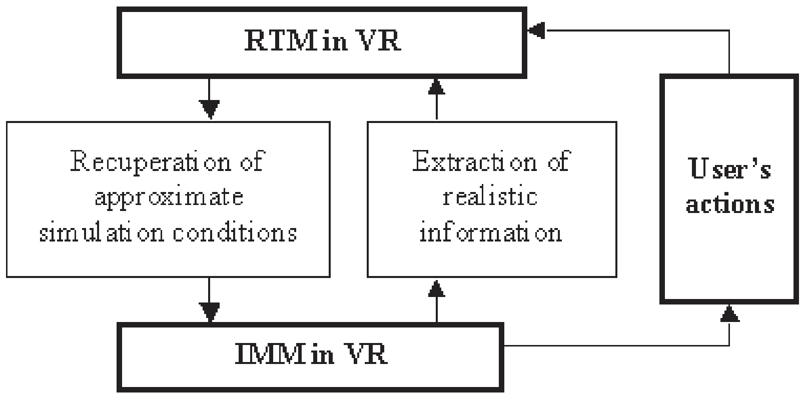

Fig. 1. New architecture of simulation environment for assembly operations involving flexible parts.

First of all, the deformation of the flexible part based on the real-time mechanical model is generated and monitored through current VR devices. This model, described in [4,12] and detailed in [14], is based on a dual approach applied to a series of bar networks of constant topology associated to a surface representation of the flexible component. Various functionals have been set up to express different mechanical behaviours like bending, buckling, etc. and compute the equilibrium position of the corresponding bar network. The surface model is of B-spline type and its control polyhedron vertices are used to define the bar network of the real-time mechanical model. This model can be subjected to position or force constraints. Position constraints are used to match the input of VR trackers devices and to update this model with output from the interactive mechanical model. From the surface model, a facetted representation is fed into the graphics engine of the VR system. Previous works and integration into the Virtual Design 2 software have shown that a frame rate of 10 frames/s using a SGI Onyx workstation can be achieved with this model. Due to the dual approach used in this model, the forces applied to the structure are fictive and hence cannot be helpful for A/D simulations. This model does not use the concept of strain and do not refer to behaviour law of a material.

Then, the operator can trigger interactive models to estimate realistic displacements and/or forces when the real-time model becomes not accurate enough, i.e. the geometric information (positions of key points, length of the flexible component to be designed, etc.) differs too much from the real dimensions of the component. It is necessary to retune the real-time model with interactive one so that the simulation process can proceed with a new range of configurations to evaluate the A/D process in terms of ergonomy using realistic values of forces and/or displacements, to check accurately the lack of interferences between the manipulated component and its exterior environment using the equilibrium position generated by this interactive model. Hence, the real-time assembly planning model can be used to feed the interactive mechanical behaviour simulation model (Fig. 1).

According to the A/D simulation conditions obtained through the real-time module of the VR environment (load to be applied by the operator, position of flexible part), the interactive model of flexible part should produce force and geometric data. Such a model is based on a non-linear behaviour of flexible beams with non-linear boundary conditions. Finally, these data will feed the real-time module generation phase of VR environment using the neutral line equilibrium positions and the section orientation that can be deduced from them. Conversely, positions of key points for the real-time model can be used to feed the interactive model through VR trackers to estimate realistic deformed shapes. Thus, the interactive system can take advantage of the real-time environment whereas the real-time system can exploit the result of a simulation to visualize forces, update a real-time deformation model for a local range of use of the flexible component until another simulation may be requested by the user.

The non linear model is now described in more details since it is a new development contributing to the proposed architecture.

5 Example of interactive mechanical behaviour model

To emphasize the importance of the mechanical model elaboration of the flexible parts in A/D context, a model based on [15–17] has been set up. It focuses on the complex behaviour of the flexible beam-type objects (pipes, hoses, strings, ropes, etc.) under various load cases in 2D because this is probably the most important class of the flexible parts in the A/D operation process.

The geometry of such objects can be expressed by sweeping of a circular section along the neutral line. Thus, this mechanical model relies on the behaviour of the neutral line, which can be represented by a "flexible line".

Despite of the diversity of load cases, from the manipulation point of view of such objects in a VR environment, it seems efficient to bound this variety and consider the most important loads taking into account some specificities of A/D operations. As an example, a typical operation can be reduced to the following scenario: when one end of the pipe is free (disassembled) and the user wishes to

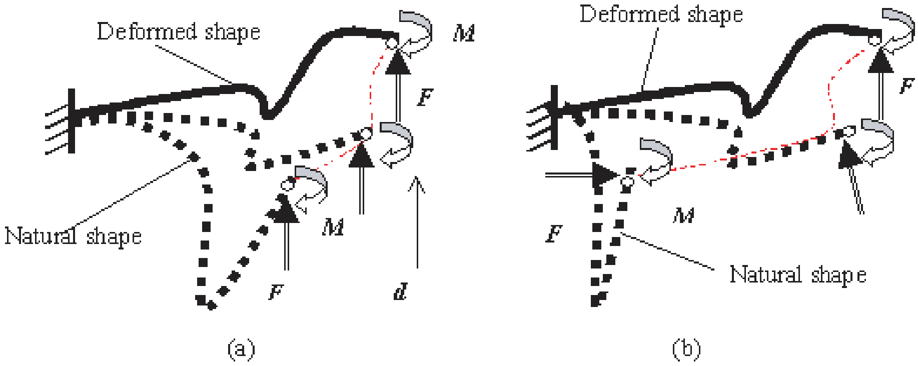

Fig. 2. Examples of considered load cases for A/D operation simulation: (a): preservation of force direction d; (b): preservation of an angle between force direction and the beam neutral line.

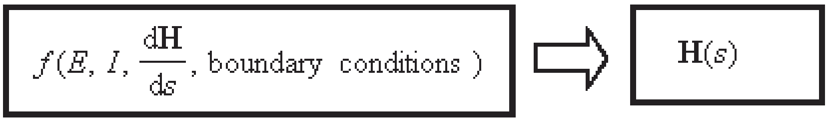

Fig. 3. Global calculation scheme.

fix this free extremity or get access to another component hidden by this pipe, the user applies a large flexion to the pipe by loading its free extremity (Fig. 2).

Under the action of external forces, the flexible part deforms and the equilibrium equations are always valid but they will be written for a deformed structure. In fact, the large displacements of the component generate non linear boundary conditions, i.e. force locations move during the deformation process. Thus, the independence principle of the effect of deformations and forces applied to the object is not longer valid with large displacements. Assume that:

- materials are homogeneous, isotropic and used in the elastic domain,
- the beam is not extensible,
- beam sections stay orthogonal to the neutral line during the deformation process,
- length and curvature radius of the neutral line are large with regard to the section dimensions.

It is possible to obtain, using the fundamental theorem of mechanics so that a material system is in equilibrium, a ordinary differential equation system characterising perfectly not only the flexible beam mechanical state but also supplying the user the beam geometric shape under given boundary conditions. Namely, in 2D space, an expression of the flexible beam state vector derivative is obtained:

$$\frac{d\mathbf{H}}{ds} = \frac{d}{ds}\left[x, y, \theta, N, Q, M\right]^{\mathrm{T}} \tag{1}$$

Globally, the differential system can be represented as a function of input data (different user's actions or calls of the real-time assembly planning model from the VR environment) and output result of flexible beam behaviour (Fig. 3).

It should be noticed that the boundary conditions at two points are required to solve the equation (1), and no concept of mesh is required to generate the solution. Hence, these boundary conditions (geometric and force limitations) may be specified either by the user or the real-time model of the VR environment during the manipulation and/or A/D sequence evaluation to produce realistic forces or movements.

In fact, a state (force and configuration) space definition is introduced. A mechanical system state can be defined as:

- the force space (i.e., the mechanical system is subjected to force boundary conditions) so, the "system answer" will be found in the configuration space (a geometric shape will be computed),
- the configuration space (i.e., the mechanical system is subjected to geometric boundary conditions) so, the "system answer" will be found in the force space (necessary forces will be evaluated to reach a prescribed geometric position).

Hence, among the different simulations, three main categories can be distinguished as relevant for the virtual A/D simulation of flexible part behaviour (Fig. 4, for more details see Tab. 1):

- case 1: one end of the flexible beam is fixed and the displacements of this beam will be computed under a given load during the design process (the system answer will be found in the configuration space),
- case 2: application of two forces to mimic two human hands with preservation of angles between the force directions and the neutral line during the A/D operation simulation (the system answer will be found in the configuration space),
- case 3: one end of the flexible beam is fixed, the coordinates of the hole corresponding to the assembled beam position are known and the forces/moments to be applied to reach a prescribed geometric configuration

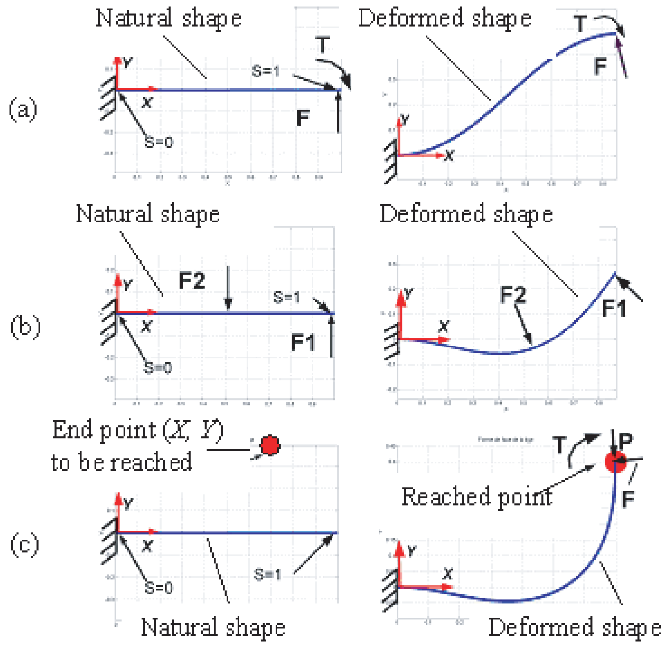

Fig. 4. Principal tasks for flexible beam behaviour simulation in the virtual A/D context: (a): simulation case 1: deformed shape computation under an adimensional load defined in the force space: $F = 7$, $T = 3$; (b): simulation case 2: deformed shape computation under an adimensional load defined in the force space: $F_1 = 7$, $F_2 = 15$; (c): simulation case 3: deformed shape computation and forces F and P and momentum T evaluation to reach a prescribed adimensional end point position fixed by the user in the configuration space: $X = 0.7$, $Y = 0.4$.

Table 1. A/D simulation configuration with corresponding adimensional boundary conditions represented in Figure 5.

simulation cases	space where the system answer will be found	boundary conditions: $s = 0$	boundary conditions: $s = 1$	algorithm CPU time, s
case 1	configuration space	$x = 0$ $y = 0$ $\theta = 0$	$N = 0$ $Q = F$ $M = T$	0.1
case 2	configuration space	$x = 0$ $y = 0$ $\theta = 0$	$N = 0$ $Q = F_1$ $M = 0$	0.4
case 3	force space	$x = 0$ $y = 0$ $\theta = 0$	$x = X$ $y = Y$	0.7

will be computed (the system answer will be found in the force space).

Also, during the deformation simulation, the beam can encounter rigid or flexible obstacles on its trajectory, what complicates not only the handling of leading case but also the model to be worked out. In fact, the interactive simulation system will need to know dynamically the parameters of possible contacts and the values of contact forces to generate the realistic movements of the manipulated part and the possible deformation of flexible obstacles. The numerical experiments presented have been performed in a space free from obstacles. The real-time mechanical model already incorporates contact boundary conditions between a flexible part and rigid ones [4].

The numerical tests have been accomplished on a Dell workstation with a Pentium III processor 900 MHz using the boundary value problem solver for ordinary differential equations in the Matlab 6.1 environment. The algorithm is based on the simplified Newton (chord) method and exploits the collocation Simpson method for integration with error estimation and mesh selection from the residual at the middle of each subinterval [18].

6 Conclusions

The different problems met during the A/D simulation processes using various methods have been discussed. As a consequence, a new architecture of the simulation environment for the A/D operations has been proposed to take into account the complexity of the flexible component behaviour into the virtual assembly process. The proposed architecture and models aim at supplying the elements to perform simulations applicable to flexible objects (beam-type objects) used into an A/D context based on VR technologies.

The current real-time and interactive models form two complementary levels to handle deformation models of progressive accuracy. In fact, the interactive system can take advantage of the real-time environment to get user-defined positions while supplying the user realistic forces and displacements estimations to perform the adequate simulation whereas the real-time module can exploit the result of this simulation during the virtual A/D operation and so, serve a basis in the visual evaluation of the A/D sequence sets. Both models have been evaluated with data from an oil hose provided by BMW during the European project DMU-VI [2]. These models, compared with experimental data, have generated very satisfactory results and proved their efficiency.

The numerical experiments proposed show the real possibility to compute realistic forces and geometric configurations in fairly interactive time (CPU time ranges from 0.07 to 2 s depending on the problem complexity). This can have considerable influence on the reduction of the product design cycle as well as the number of necessary physical prototypes to test the assemblability involving flexible part behaviour.

Next steps of the work will focus on the generation of mechanical models for the 3D case to take into account the complexity of the environment of flexible parts, possible contacts between manipulated parts and already assembled rigid or flexible components, other user's force and geometric boundary conditions meeting more precisely in the practice of the A/D operation process.

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