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# Interactive assembly simulation with haptic feedback

Jerome Perret  
*Haption SA*

Judy M. Vance  
*Iowa State University, jmvance@iastate.edu*

Georges Dumont  
*Ecole Normale Supérieure de Cachan*

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# Interactive assembly simulation with haptic feedback

## Abstract

### Purpose

– The paper aims to present interactive simulation with haptic feedback as a valid method for solving complex assembly problems in the context of industrial product development. Its purpose is to clarify the position of interactive simulation with respect to other methods, and to emphasize its specific value for design engineers.

### Design/methodology/approach

– The paper describes the challenges faced by design engineers in the context of design for assembly and assembly process planning. It introduces and compares automatic path planning and interactive simulation as two different approaches for checking the feasibility of assembly tasks. It provides a review of the scientific challenges and technical issues faced when implementing interactive simulation with haptic feedback in this context. It presents recent research results in the domains of final insertion and human model simulation.

### Findings

– The paper provides an overview of the scientific, technological and practical aspects of interactive simulation with haptic feedback. It explains how this method benefits from the manual skills and cognitive capabilities of the human operator for solving complex assembly problems. It proposes an assessment of the technical maturity using the Technology Readiness Level approach.

### Originality/value

– The paper gives insights about the maturity and usability of interactive assembly simulation with haptic feedback, for the benefit of design engineers seeking new ways to decrease product development time and costs while increasing quality.

### Keywords

Assembly simulation, production planning, design for assembly

### Disciplines

Computer-Aided Engineering and Design | Graphics and Human Computer Interfaces | Manufacturing

### Comments

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## Interactive Assembly Simulation with Haptic Feedback

Jérôme Perret  
Haption SA, France  
[jerome.perret@haption.com](mailto:jerome.perret@haption.com)

Judy M. Vance  
Iowa State University, USA  
[jmvance@iastate.edu](mailto:jmvance@iastate.edu)

Georges Dumont  
IRISA, France  
[georges.dumont@irisa.fr](mailto:georges.dumont@irisa.fr)

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*Findings* – The paper provides an overview of the scientific, technological and practical aspects of interactive simulation with haptic feedback.

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**Paper type** Technical paper

### **1. Introduction and problem statement**

Design for assembly and assembly process planning are very important steps in the development of a new industrial product. If not done properly, they can lead to extremely high added costs, resulting from unrecognized need for specialized assembly equipment, overlooked efficiencies in operator workstation layout, or the inability to assemble components according to the prescribed assembly procedure. They also impact the duration and cost of maintenance activities.

During the development process, the assembly or maintenance procedures need to be verified for coherence with the current state of design of the product. The verification can be done with real prototypes and virtual models. Today, it is possible to ensure product quality and to evaluate a large number of potential designs using technologies like rapid prototyping and virtual validation, while reducing time-to-market.

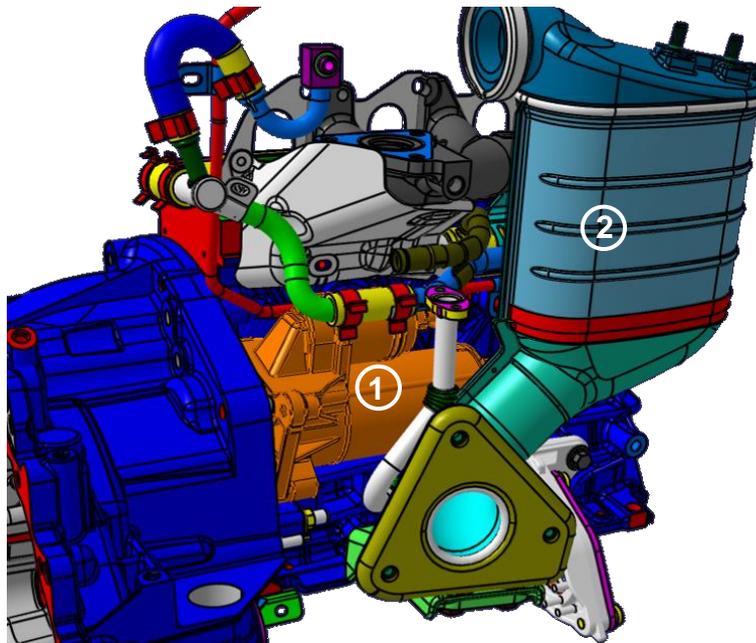
In the early phases of product development, no physical parts exist which can be manipulated to validate assembly tasks. One approach is to check the feasibility of each individual assembly step using methods of Digital Mock-Up (DMU), such as measurements, sectioning and clash detection. Additional tools are also available to simulate the behaviour of materials, like flexible components, and to include static positioned virtual human models into the virtual world. Because these tools rely on simulating the assembly process, the resulting visualisations and measurement resulting from each simulation have to be

evaluated by an assembly expert. Even with careful evaluation, some problems may be overlooked which could lead to significant costs during manufacturing or maintenance.

Another approach is to perform an assembly trial with virtual models. Tools like motion capture of the human body and different kinds of input devices with haptic, tactile and acoustic feedback have been developed to make virtual assembly validation more realistic. In this case, simulation and validation can be performed at the same time. Because of the linking of simulation and validation, problems related to direct perception could also be identified by non-experts. This paper presents two different tasks of assembly validation: path finding during part positioning and human accessibility and field of view.

### ***Path finding and assessment of collision freedom during part positioning***

In this first case, the objective is to assess the feasibility of the assembly task by finding a collision-free path for the part to travel during the assembly. If no collision-free path exists, then it is important to identify bottlenecks and collisions so that the product or process can be modified. Additionally, the method should provide means to assess if the assembly can be done in a reliable way on a production line. Figure 1 shows an example of a complex assembly task.



**Figure 1:** Can the starter engine (1) be removed and replaced without removing the air filter (2) first? **Source:** 3D model by courtesy of Renault SAS

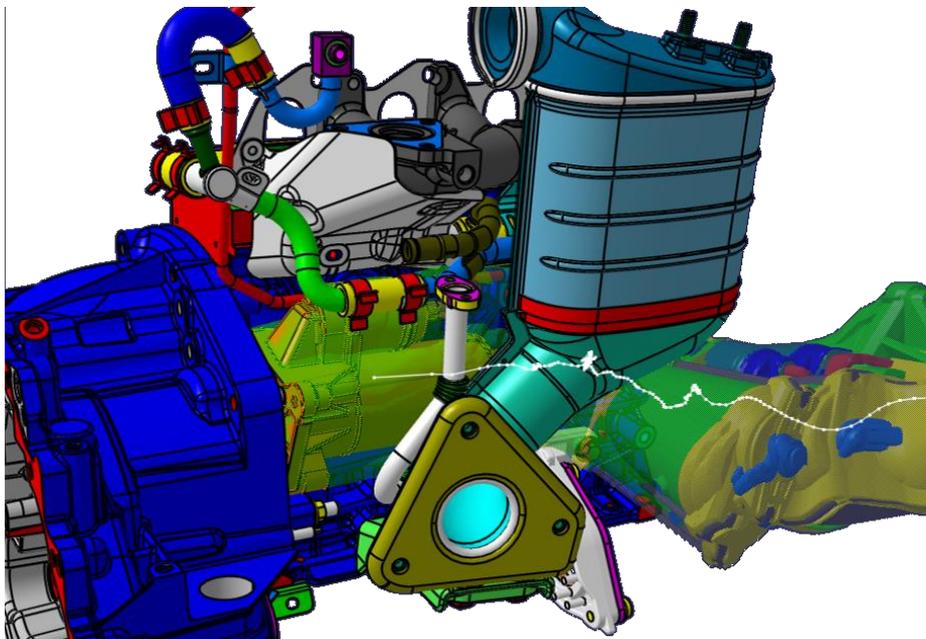
Two techniques exist which work directly on the 3D model: automatic path planning combined with methods of Digital Mock-Up (DMU) and interactive simulation with haptic feedback.

Automatic path planning is a completely automatic process, which explores the configuration space of the moving part and looks for adjacent points without collisions. It builds a graph of all adjacent collision-free points, until it is able to fit the final assembly point inside the graph (Ferre *et al.*, 2005). The most efficient method is probabilistic: it shoots configurations at random and tries to find collision-free paths between them. Depending on the complexity of the environment and the additional constraints given by the user, the process of developing the graph can take between a few minutes and several hours. One problem is that in the same assembly scenario different paths could be calculated because of the probabilistic method. By analyzing them, different bottlenecks will also be found. Better algorithms will find

the optimal path, in which every point has the best distance (clearance) to other parts. It is also possible to configure negative offsets to see the collisions in the path if no collision-free path was found.

The second technique, interactive simulation with haptic feedback, reproduces the same kind of experience that the design engineer would have if the physical prototype of the product were being evaluated. In short, it simulates human interaction with the 3D model. It calls upon the cognitive abilities and understanding of spatial relationships of the design engineer, rather than the computational power of a computer. Through the haptic interaction, the user can make full use of manual skills, in order to identify bottlenecks, evaluate clearance and explore possible improvements.

Once a satisfactory collision-free path has been found, a "swept volume" can be computed, which is composed of the union of the volumes of the part as it moves through a defined path. The swept volume can be added to the 3D model with the instruction not to add any other part inside that volume (Figure 2).

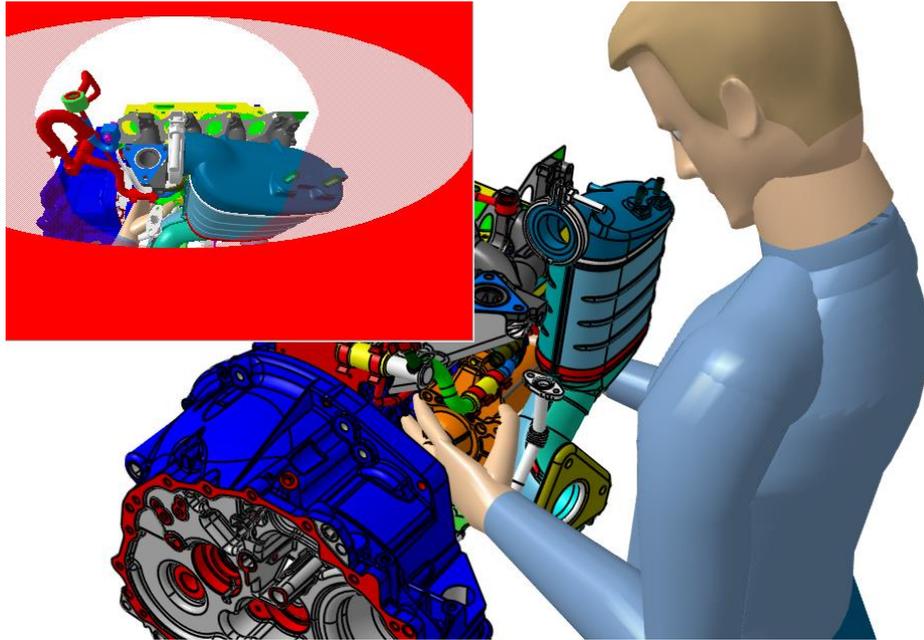


**Figure 2:** Collision-free path for the starter engine (white) and swept volume (transparent)

### ***Positioning of human model and assessment of accessibility and field of view***

In this second case, the objective is to evaluate whether the assembly can be done by a human operator in good conditions. There should be enough room for the hands of the operator to move without a risk of injury, and with an acceptable level of strain on in muscles and joints. Moreover, enough of the assembly area should be visible in order to ensure the correct positioning of the part and guarantee the quality of the operation. Furthermore, the operation should be validated for operators of different sizes, reflecting the population of the assembly line workers.

The static positioning of human models can provide preliminary answers to those questions (Figure 3). The procedure can be extended by automatic movement planning of the human body in order to represent a whole assembly step.



**Figure 3:** *Static positioning of a human model and evaluation of the field of view*

Alternatively, the movements of a virtual human body can be controlled interactively by a design engineer or an actor using motion capture with different tracking techniques. In the case of a complex scenario, it is necessary to provide some kind of physical feedback to the actor, so that fine motoric movements of the hands can be controlled. Here again, haptic interaction is needed.

In addition to the swept volume, the sequence of movements of the human model can be integrated into the 3D model as a record of the interactive simulation. Depending on the needs, posture-based ergonomic analyses or cycle time evaluations can be carried out on those sequences.

## **2. Requirements of haptic interaction**

A haptic device, also sometimes called a force-feedback device, is a computer peripheral, which can apply forces to the hand of its user (Figure 4). Haptic interaction is highly bidirectional: the user inputs information into the system through the movement of the haptic device end effector, and at the same time the user feels the system output as a force. In the context of this article, the task involves the user picking up an object and trying to fit it into a complex assembly, feeling the weight of the object and the contact forces with other objects.



**Figure 4:** *Haptic device Virtuoso 6D*

The laws of physics govern the way objects behave; therefore, to achieve fidelity in a haptic simulation, the forces are computed based on the mathematics of physics. Especially in the case of an assembly simulation, the user is expecting the 3D model to behave as in real-life. For example, rigid objects must not interpenetrate each other and objects must be able to slide when surfaces contact.

Because of the nature of haptic devices, the physics simulation must be programmed so that it produces stable forces in real-time at a high frame-rate. To maintain stability, haptic simulations attempt to calculate forces at the rate of 1 kHz. The requirement of a 1 kHz frame-rate is not related to the capacity of the human sensory system (at such a high frequency, humans are unable to sense the direction of a force), nor to the performance of the task (assembly operations are usually done at low speed). This requirement comes as a direct result of the control theory, which states that the maximum stiffness in a closed-loop system is inversely proportional to the square of the regulation period. As a consequence, the maximum stiffness of a system running at 500 Hz will be 4 times lower than that of the same system running at 1 kHz. The result is that with a frame-rate significantly lower than 1 kHz, all rigid objects feel like very soft rubber.

For the purpose of this article, we will confine ourselves to rigid body simulation, which is a well-defined subcategory of the general problem. Interactive rigid-body physics simulation depends on two main building blocks: collision detection and movement integration. We will discuss the second part first, so as to simplify the discussion on collision detection.

### **3. Movement integration for interactive assembly simulation**

In a physics-based simulation, the movement integration consists basically of solving Newton's laws of motion to determine the position of objects that have been acted on by a force. Some positions are easy to compute, for example, the effect of gravity forces on an object. But, in the case of physics-based simulation of assembly methods, we are primarily concerned with calculating the contact forces between objects.

As two objects collide, opposing forces are generated according to Newton's third law of motion. There are two common methods to calculate these contact forces. The first consists of "penalizing" the contact forces, i.e. replacing them with linear repulsion forces as functions of the distance between objects (Hasegawa *et al.*, 2003; Hasegawa and Sato, 2004). Therefore, as one object approaches another, the resisting force increases linearly as the distance between the two objects decreases. The result is that the operator feels a hard force upon contact. The penalty method is fast, easy to implement, and gives good results in simple configurations. However, in case of complex situations, typically when several objects have many points of contact together, it can result in unrealistic behaviour such as unconstrained movement or vibrations. Moreover, it does not provide an easy way to compute contact friction, so that the objects feel very slippery.

The second method, called "constraint-based", consists of writing each contact as a unilateral constraint, and solving the resulting system of equations for the object positions (Tching, 2008a, b; Sauer and Schomer, 1998; Renouf *et al.*, 2005). The constraint-based method is much more difficult to implement, and takes a lot of time to compute, especially as the number of contact points is large. Obviously, it produces much more realistic results, without unwanted artifacts and with the possibility to compute contact friction correctly. In the case of assembly simulation, it is bound to replace the penalty method eventually, but the performance issues are very challenging. One of the main difficulties is that the numeric solver cannot be easily parallelized, and thus doesn't benefit from the development of multi-core CPU architectures.

Both methods result in interpenetrations between objects, albeit temporary and small. In the context of assembly simulation we are looking for a collision-free path, therefore interpenetration is not allowed. As a consequence, contact information should be generated before the geometries actually collide.

#### **4. Collision detection for interactive assembly simulation**

Collision detection is the act of determining of when two bodies contact. In the case of automatic path planning, the problem of collision detection is reduced to the question: is there a collision between these two geometries? No more information is needed than the existence of a collision. For example, it can be enough to determine whether a surface exists (e.g. a plane) which separates the two geometries.

In the case of interactive physics simulation, additional information is needed in order to compute penalty forces or unilateral constraints. Depending on the methods used, the simulation also needs the interpenetration depth, the intersecting volume, or the minimum local distance of separation. In addition, to calculate the new position of the object, the movement integration algorithm needs to know the point of contact and a normal vector to the contact.

One of the oldest and still most efficient methods (in terms of computation time) is called Voxmap PointShell (VPS). It relies on an asymmetric representation of objects, so that the collisions are detected between object pairs. In each pair, one object is considered as fixed, and is represented as a Voxmap or map of voxels, the other is mobile and represented as a PointShell or shell of points and normal vectors. In order to test for collisions, each point of the PointShell is projected into the Voxmap. If it is found to be inside a voxel, then a penalty force is computed which lies on the normal vector (McNeely *et al.*, 1999; McNeely, 2006). In order to avoid interpenetration, VPS embeds the voxel representation of the object into a larger Voxmap. As two parts approach each other, a proximity evaluation is performed. A resistive braking force is applied when objects get close and the penalty function is active before the objects interpenetrate.

VPS is very efficient, and has many advantages. For example, because it is based on a voxel representation of geometry, it is very robust to the effects of potential bad quality of geometric information (such as holes, duplicate edges, inverted normals, etc) contained in some CAD models. Thanks to the additional layers of voxels, it can also handle pure surfaces correctly (i.e. without volume). However, the haptic feedback is poor, and some artifacts can occur, especially when the assembly is very constrained. The method has been improved by many authors (Renz *et al.*, 2001), without removing all the drawbacks (Barbič and James, 2007; Sagardia *et al.*, 2008).

Another method has been proposed, often called "continuous collision detection", which attempts to determine the exact instant of contact between two computation frames (Redon *et al.*, 2001; Zhang *et al.*, 2007). Instead of trying to locate the points of contact, it uses a fast clash detection algorithm; in case of a clash appearing between two time steps, it computes the relative motion between the two objects since the last step and backtracks along it until it finds a clash-free position; then it uses that position and the relative movement as a unilateral constraint, which is then fed into the (constraint-based) movement integrator. The main benefit of that method is to reduce the number of unilateral constraints, so that the integration of the movement can be very fast, although it is constraint-based. It was used in an operational context in industry for several years (Redon *et al.*, 2001), but was abandoned because of the lack of commercial support. It is unclear whether it could handle multiple moving objects or not.

Yet another method is based on computing the local minimum distances (LMD) between two objects (Johnson and Cohen, 1998). It relies on an internal representation of the object geometries, using spheres and cones. Each sphere is centred on a vertex, and the corresponding cone is aligned on the normal vector at the same vertex. A potential LMD is detected when two spheres belonging to two different objects intersect and their respective cones are facing each other; if that is the case, then the method fetches the actual local geometry (the triangles) and performs a brute-force computation. The method requires very clean geometries, with a very dense mesh and well-oriented normal vectors. It is usually used with a constraint-based movement integrator; however, since it produces many more constraints as the exact contact method presented above, it is slower and thus less suitable for haptic interaction.

A promising method, developed very recently, creates an internal sphere packing of the objects, and uses the hierarchy of spheres in order to determine contact conditions in a very fast process (Weller and Zachmann, 2009). Depending on the need of the application, it can produce interpenetration depth, intersecting volume, or local minimum distances. It has been successfully applied to haptic interaction with multiple non-convex moving objects, and showed to perform better than VPS. It is yet unclear whether it can handle thin objects effectively or not.

## **5. The problem of final insertion**

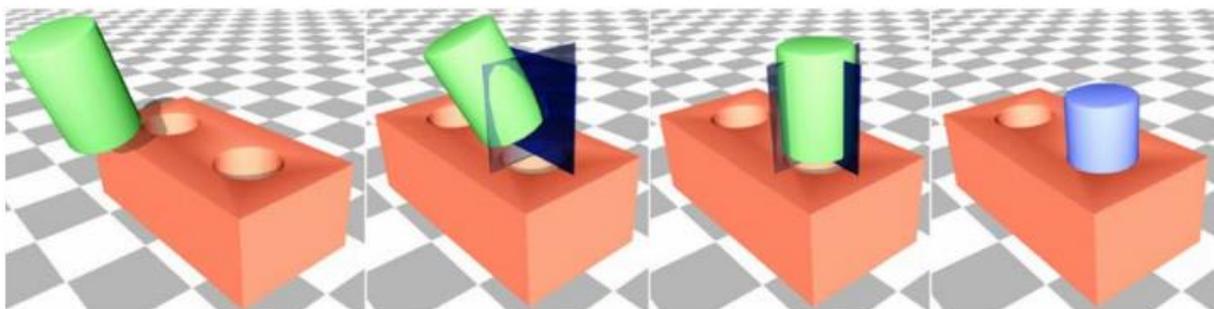
Implementing movement integration and collision detection provides the user with a simulation environment that closely mimics the real world during the task of manipulating objects. However, in the final step of object insertion, additional issues are encountered. Of all the methods described above, the exact contact method is the only one, which provides haptic feedback at the exact point of contact. In all other cases, the haptic feedback occurs before the actual contact, or after collision with an external proximity shell, introducing imprecision in the contact simulation. Sometimes, it is possible to set an upper bound on the imprecision of the contact, but it is usually in the millimetre range. The result is that it is

impossible to rely on collision detection for the final insertion of a part if there are low assembly clearances involved.

One promising approach is to use a hybrid method where traditional simulation of contact and motion are implemented for free movement and fixed assembly constraints, which are easy to integrate into the physics simulation solver, are implemented during final insertion (Vance and Dumont, 2011). The assembly constraint can be defined by the user, extracted from the CAD model, or determined automatically by the simulation system through the analysis of the geometry (Seth *et al.*, 2010; Iacob *et al.*, 2008, 2011; Boussuge *et al.*, 2012).

The challenging issue of the hybrid approach is developing an algorithm to account for the switch between the free motion simulation and the assembly constraint simulation. Several solutions have been proposed. Vance uses a blending algorithm, which transitions the user between free motion and constrained motion (Seth *et al.*, 2010). Picon also studied different attraction fields and evaluated suitable laws (Picon *et al.*, 2008).

Tching defines virtual geometries (planes), which help the user to find the right alignment on the assembly constraint (Figure 5) (Tching *et al.*, 2010). After the correct alignment has been reached, the assembly constraint is activated in the physics simulation solver, and the collision detection is switched off, so that the final insertion can be performed interactively. However, switching off collision detection altogether is not satisfactory, as a contact with geometry outside of the insertion area could oppose the movement. It would be better either to deactivate collision detection within a limited volume around the insertion area, or to ignore contact points within the same volume. As of today, no article has been published which solves that problem.



**Figure 5:** Using virtual geometries to guide the alignment of the part on the axis of the assembly constraint.

## **6. Human model simulation**

Until now, we have discussed the problem of assembly simulation in the context of path finding. The next challenge is to achieve a simulation of the whole assembly process, including the operator doing the task, the tools used for fixing the parts, etc. Here, it is necessary to include some position tracking equipment to capture the current posture of the operator in real-time. Different solutions can be purchased off-the-shelf, including optical, mechanical or inertial measurement, or combinations of those.

Next, a human model is needed to serve as an avatar of the operator. For the purpose of haptic interaction with the 3D model of the product, it is necessary to choose a physical model, which can be integrated into the movement solver. Several human models exist on the market and in the scientific community, covering different aspects of the needs for human simulation. As an example, the Safework model, integrated in the V5 solution of Dassault Systemes, is composed of 94 rigid bodies linked together via 131 rotary joints. Each rotary

joint can be expressed as a bilateral constraint, composed of a rotation axis and a minimum and maximum joint angle.

The technical challenge of the simulation is increased significantly by the introduction of the human model: instead of computing the motion of a few rigid bodies with a limited number of contact points, the physical integrator is now juggling with almost a hundred moving objects and many more constraints. Practical issues are also faced, such as the need for a perfect co-localisation of the haptic device and the motion capture system. It is also necessary to provide the operator with a visual display of the virtual environment during movement, so that a simple screen is not sufficient: a head-mounted display or a CAVE™ is called for (Figure 6).



**Figure 6:** First author simulating an assembly operation inside a car. **Note:** The head of the human model is hidden in order to optimize the view through the head-mounted display.

## **7. Technology readiness level**

Before we conclude, we feel it is important to provide the reader with an insight about the maturity of the technical solutions presented in this article. A well-known maturity assessment tool is the "Technology Readiness Level" originally developed by NASA in the 1980s for space-flight systems (Wikipedia, 2013). It was later adopted by the US Air Force, and expanded in order to encompass other types of technologic components.

Using the TRL descriptions for hardware and software proposed by William, 2003, we would assess the maturity of interactive rigid-body assembly simulation with haptic feedback as follows:

- Path finding: TRL8, i.e. "technology proven to work in its final form and under expected conditions".
- Final insertion: TRL5, i.e. "the basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment"
- Human positioning: TRL6, i.e. "representative model or prototype system, which is well beyond that of TRL5, is tested in a relevant environment"

## **8. Conclusion and future work**

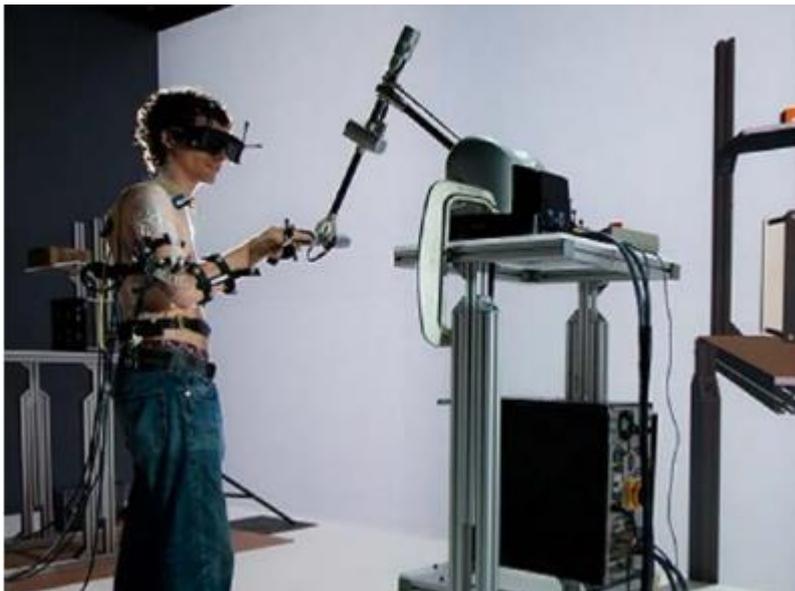
Assembly planning is a critical operation during the course of product design. In many cases, the feasibility of the assembly cannot be decided on a simple visual inspection of the 3D model, and more complex investigations are needed. Interactive simulation with haptic

feedback recreates a physical interaction with the 3D model, calling upon the manual skills and cognitive capabilities of the human operator. By performing the assembly operations "hands-on", the design engineer or the process planner measures the complexity and evaluates also the ergonomic dimension of the tasks.

In this article, we have discussed the main issues faced when implementing an interactive simulation with haptic feedback. We have explained the challenges of movement integration, collision detection, and switching to assembly constraints. We have finally discussed the integration of a model of the worker and given an insight on the maturity of the technology.

One of the major challenges to be addressed in the future is the introduction of deformable objects. Indeed, many of the parts composing an industrial object are deformable, and need to be deformed in order to be assembled (for example electric cables, hydraulic hoses, rubber seals, leather furnishings, etc). The human skin is also a good example of non-rigid material, and the modelling of its deformation is mandatory for a good simulation of grasping tasks.

Another direction for future work is the introduction of additional sensors on the operator while simulating an assembly task, in order to measure the muscle activity and evaluate the physical strain incurred (Figure 7).



**Figure 7:** Operator equipped with electromyography (EMG) sensors

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