In Proceedings of the 9th ESA Workshop on Advanced Space Technologies for Robotics and Automation
'ASTRA 2006' ESTEC, Noordwijk, The Netherlands, November 28-30, 2006

Advanced force-feedback solutions and their application to space programs

Jérôme Perret, Pierre Vercruysse
Haption S.A.
Atelier Relais ZA Route de Laval
53210 Soulgé-sur-Ouette, France
Email: jerome.perret@haption.com, pierre.vercuysse@haption.com

INTRODUCTION

In this paper, we describe how the emergence of industrial applications of haptic technologies, and more specifically of force-feedback devices, opens new perspectives for space programs. First, we describe recent breakthroughs of force-feedback solutions for interaction with the digital mock-up in Virtual Reality. We present the principles of force-feedback, starting with remote manipulation such as in the nuclear industry, and following with interactive real-time physic simulation in a CAD environment. Then, we explain how those solutions help reduce design time and costs, and improve quality and maintainability of the future products. We give precise examples and success stories coming from major European automotive and aerospace manufacturers, outlining the benefits as reported by the users. Finally, we focus on potential applications to the space programs.

As a complement to the talk, we propose a hands-on demonstration of the technology, illustrated on a real use case for the automotive industry.

FORCE-FEEDBACK: FROM REMOTE OPERATION TO VIRTUAL REALITY

The first force-feedback devices appeared in the early 60s in the USA, to address the needs of the scientists working on nuclear fission for energy supply. The production of fuel in large quantities and the development of industrial processes for the future nuclear power plants, called for the development of solutions to protect personnel from irradiation. The standard set-up, still used today, was to confine radioactive materials in an airtight chamber, and manipulate them remotely (at a few meters' distance) through cable-driven systems similar to pantographs. Because of the non-repetitive nature of the operations, and the needs for intelligent reactions in case of incident, it was not possible to use purely automatic systems, and the man-in-the-loop approach was considered the only solution, as is still the case today. Force-feedback means the possibility for the user to feel the forces exerted in the remote environment. It was not at all a new concept, as the driving wheel of a car and the stick of an airplane are both "feeding back" forces to the driver or pilot.

For the nuclear industry, the first benefit of force-feedback is the ability to control the forces, hence avoiding damage to the equipment. The second advantage is that force-feedback complements vision, which can be impeded by radiation-screening devices (the typical set-up includes a one-meter thick bay filled with lead-charged oil). However, pure mechanical transmission has a number of disadvantages, like the distance limitation and the need for an open port in the airtight cell, which may cause leakage. Those were the main drives for the development of new generation force-feedback systems, based on analogic and then digital transmissions, which has been going on for more than thirty years [1][2]. In the 90s, thanks to the increased performances of computers, researchers proposed to replace the remote environment with a simulation [5]. The first idea was to address the needs for training of nuclear operators. However, they soon realized that such a technology could find many more applications, and the first "haptic" devices were born [3][4].

The real power of haptics is the ability for the user to "physically" interact with a simulation. As a general rule, the operator uses the haptic device to "navigate" in a virtual space (which can be a 3D scene or a representation of some data, such as the results of a fluid dynamics computation), and feel some constraints applied to his movements (such as the contact with virtual objects, or the direction of a gradient in the data values). Most important is the nature of the interaction, which is very intuitive and natural for most users. As a consequence, work with a haptic device is very efficient, even for untrained people. Still, haptics have found very few applications on the market today, due to the complexity of the simulation itself. One of those is virtual sculpture, which is used by companies for the intuitive 3D design of products for the consumer market (shoes, toys, figurines) [6]. A second one is the simulation of assembly or maintenance operations in Virtual Reality.

FORCE-FEEDBACK FOR VIRTUAL PROTOTYPING

With the ever increase of competition in a globalized market, industrial companies are looking for ways to reduce product design time and costs. The on-going trend is to replace physical prototypes with one single "digital mock-up", defined as the complete set of technical data representing the product under development. In principle, it costs nothing to build, it is always up-to-date, and it is completely traceable. Using advanced simulation techniques, it is possible to carry out aerodynamic analyses, ergonomic studies, crash-tests, market surveys, etc, directly with the digital mock-up. However, some operations are very difficult to validate without a physical interaction. That is typically the case of assembly/disassembly and maintenance.

The problem addressed by assembly simulation is to find the most efficient way to manufacture the product by putting all of its components and subsystems in the right place. The efficiency is defined by many different criteria: cost, time, quality, but also optimal use of the infrastructure (e.g. the assembly line), of the operators' competences, etc. Although there are some tentative implementations of automated assembly planning, the actual work relies heavily on human skills and expertise. Only the human brain is capable of integrating many constraints and analysing the problem in all its complexity. The same is true for maintenance simulation, although the objective is different. There, the goal is to find the right procedure for exchanging one component or subsystem while removing the smallest possible number of other items.

For both applications, the core activity is the search for access paths based on the geometry of the digital mock-up. Using a mouse and keyboard, this can be very tedious and take a long time, especially when working on a highly integrated product, like a modern car engine or the cockpit of a military aircraft. With the tools available in current CAD software platforms, every movement has to be described step-by-step by setting waypoints along a trajectory. If a clash occurs (read: collision with another object), then the operator has to backtrack manually. The solution is built by exploring the free space. On a real prototype, that is not the usual case. On the contrary, the contact with other objects is sought as a way to guide the movement. No one would think of exchanging a car wheel without using the brake bracket as a guide for alignment!

The role of force-feedback is to recreate the contact information and provide it to the operator directly in his hand. Using it, he can glide and pivot very intuitively, testing different access strategies without bothering about waypoints and trajectories. After he's found a good solution, he can repeat it while recording all the movements automatically for documentation and later replay. This "hands-on" approach of assembly and maintenance simulation has many additional advantages:

- It gives more emphasis on the overall access strategy than the detailed movement tactics; therefore, atypical solutions can be found, with high gains of productivity and quality.
- It can be used by individuals not trained for using a CAD system; as a consequence, experienced workers coming from the assembly line can be involved in the design process.
- It is very demonstrative; as such, it can be used as a means to convince decision-makers that a modification of the geometry is necessary.

In France, active work on the development of interactive solutions for virtual prototyping started with the PERF-RV project [7], a virtual reality platform marshalling about twenty public and private stakeholders. Significantly, interaction with force-feedback was one of the most successful technology demonstrators produced by the project. After the closing of the platform in 2003, two different initiatives were started, with the objective of developing an industrial solution for assembly and maintenance simulation with force-feedback. The first one, driven by EADS CRC and called SAMIRA, produced an operational tool in 2005 [8], which is now in use at Airbus for the validation of maintenance operations (fig. 1). The second one, driven by CEA/List and called RIVAGE, has just achieved the release of the commercial product IFC (Interactive Fitting for Catia V5™), sold by Haption [9].

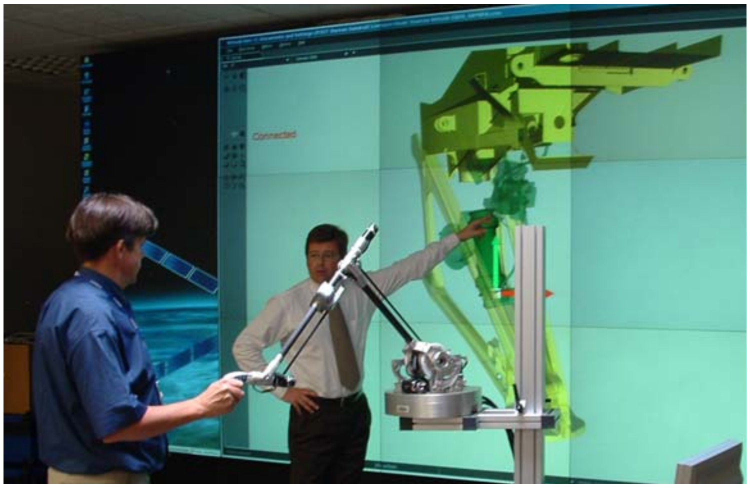

Fig. 1: Maintenance simulation with force-feedback using SAMIRA (courtesy EADS CRC/Airbus)

The RIVAGE project will continue for one and a half year, and produce more tools addressing new needs reported by the industrial partners. First of all, we are currently developing algorithms and methodologies for the interactive simulation of a virtual human operator inside the digital mock-up. With that, it will be possible to evaluate the assembly workplace from an ergonomic point of view (fig 2). We foresee that it will be applied also to the validation of driving conditions for cars and aircraft. Further functionalities will be the interactive simulation of kinematic chains (e.g. industrial robots) and deformable object (such as plastic plates, electric wires, etc.).

Fig. 2: Ergonomic study for vehicle assembly (courtesy PSA Peugeot Citroën)

APPLICATIONS TO SPACE PROGRAMS

The space industry is also a heavy user of CAD and other design tools; moreover, it relies very seldom on real prototypes for system validation. For a launcher, a satellite, or a space probe, the first system to be manufactured must be right, and sometimes it will be the single exemplary to be produced. As a consequence, the space industry will be using virtual prototyping solutions with force-feedback in the future, for assembly validation of launchers and payloads.

The simulation of maintenance activities will become an important topic for the space industry as well. The International Space Station (ISS) calls for periodic maintenance, both inside the living spaces and outside in EVA. Because weight launched to orbit is so expensive and astronaut time so sparse, every action must use the right tool and the right procedure. Further on, the in-orbit maintenance of satellites will become more casual, and again the preparation of operations in simulation will play a central role. And last but not least, the design of new reusable launchers will make intensive use of maintenance simulation, in order to reduce the time needed between flights for refitting the equipment.

Virtual prototyping techniques with force-feedback will find other uses, such as ergonomic studies for manned space missions, as well as the training of astronauts in Virtual Reality. But force-feedback will also conquer space programs in its historical implementation, as tele-manipulation devices and more generally as "human-in-the-loop robotic systems".

The most visible application will be in-orbit operation of robots for assembly and maintenance of the ISS. The impact of that technology on astronaut safety, but also on time and cost, compared to traditional EVA, will be very significant. But the future space programs will see other applications, less spectacular, but just as beneficial, in the assembly of payloads. Today, they are assembled by operators wearing protections in clean rooms of class 100000. As commercial satellites and scientific probes become ever more complex and compact, and integrate very sensitive pieces of equipment that have to be protected from contamination, the requirements for cleanliness are raised. For example, in the case of the SOHO project, the more critical sensor boxes were assembled in a class 1000 room, which required operators to wear "bunny suits" under very strict control. In the future, the use of remote-operated robots will be unavoidable.

CONCLUSION

Force-feedback technologies have been around for more than 40 years, and they have achieved a high degree of acceptance in very specific applications, such as commercial aircraft control (the A320 series) and computer gaming (force-feedback steering wheels and joysticks). They are entering a new field of use now, with the increasing demand of the industry for interactivity with the digital mock-up, the so-called "Virtual Prototyping".

In this paper, we presented this evolution, starting with the first remote-operated systems in the nuclear industry, and concluding with the latest achievements, almost available for sale today. Then, we opened a reflection about the future uses of force-feedback technologies in space programs. Virtual Prototyping in itself will be a major application, but we think that remote operation will make its come-back very soon because of requirements for safety (of the astronauts) and protection (of the payload).

REFERENCES

[1] J. Vertut, "Advances in Remote Manipulation", Transactions of the American Nuclear Society, 1976

[2] J. Vertut, R. Fournier, B. Espiau, and G. Andre. Advances in a computer aided bilateral manipulator system. Robotics and Remote Handling in Hostile Environments (Topical Meeting), Gatlinburg, TN, 1984.

[3] G.C. Burdea, "Force and Touch Feedback for Virtual Reality"; John Wiley & Sons, Inc.; 1996

[4] T. H. Massie and J. K. Salisbury. The phantom haptic interface: A device for probing virtual objects. In ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Chicago, IL, Nov. 1994.

[5] Y. Measson, R. Fournier, EVEREST: a virtual reality interface to program a teleoperated missions, IROS'97, Grenoble, France

[6] http://www.sensable.com/products/3ddesign/freeform/

[7] G. Moreau, P. Fuchs and P. Stergiopoulos, "Applications of Virtual Reality in the manufacturing industry: from design review to ergonomic studies", Mécanique & Industries 5, 171-179 (2004).

[8] G. Drieux, F. Guillaume, J-C. Léon, N. Chevassus, "SAMIRA: A Platform for Virtual Maintenance Simulation with Haptic Feedback incorporating a model preparation process", Virtual Concept 2005, Biarritz, France.

[9] T. Voillequin, "First steps of Haptics at PSA Peugeot Citroën", Special session on Industrial Applications of Force-Feedback, VRIC'06, Laval, France.