Haptic Interfaces for Virtual Prototyping

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Abstract

This paper analyzes the general requirements of Haptic Interfaces (HIs) for Virtual Prototyping operations. In particular two different paradigms of interaction with virtual objects are presented, respectively based on an anthropomorphic and a desktop Haptic Interface. The main aspects of mechanical and control system design of HIs and force rendering in Virtual Environments are discussed too. The experimental results of the simulations conducted with a force feedback arm exoskeleton are presented, pointing out the current limits of the existing devices and outlining the future developments.

1 Introduction

Virtual prototyping technologies can reduce the time and costs necessary to develop and construct new products and bridge the disciplinary and distance gaps among different collaborators working on the same project [3].
Virtual Prototyping is based on the simulation in a realistic three-dimensional Virtual Environment of the functionality expected from the new product. Before the real construction of the first prototype, it enables designers to evaluate the fulfillment of ergonomics, engineering and design requirements, and the feasibility/adequacy of the product to the foreseen usage [2]. One of the key issues in Virtual Prototyping applications is the capability provided to the operator of interacting in an efficient and sensorially sufficient way with the virtual model of the object.

The sense of touch appears to be fundamental to assess the properties of the prototype of a complex system, such as a vehicle. Although CAD systems are becoming widespread, there is still some important information that a CAD program alone cannot supply. The designer cannot see from the CAD how the operator will fit into cab or assess how the controls will feel during operation. During the development of new vehicles the designer must still wait until a mock-up or a prototype is built to find out how the controls feel and whether or not they are easy to use [1]. Vehicle simulators immersed in Virtual Environments [6][4] (see Figure 1), where either the

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contact or the inertial forces are replicated to the operator, have been successfully employed for the evaluation of ergonomics aspects in the cockpit.

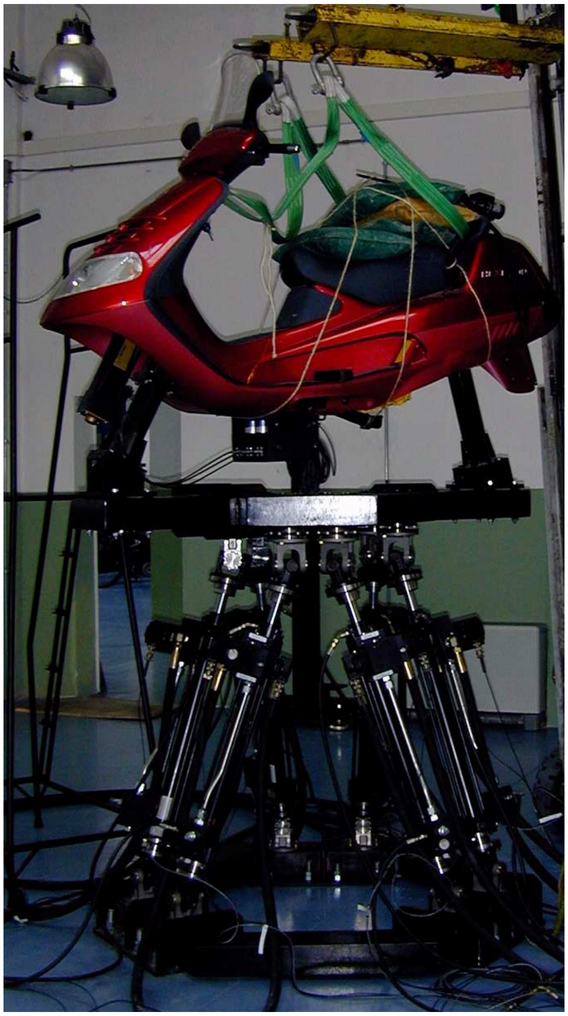

Figure 1 The MORIS motion simulator realized by PERCRO

During the design process of military vehicles, inertial motion simulators could be employed for assessing the injury potential to the truck or tank occupants, in case of explosion of anti-vehicular mines. The explosion of anti-vehicular mines represents one of the most common battlefields threats, which can cause serious injuries to the occupants, particularly to the cervical spine and legs. Possible solutions for reducing the injury potential are currently under study.

One possible solution is the equipment of vehicles with mechanically damped seats, capable of suppressing the huge vibrations induced by mine explosion. According to this approach, mechanical dampers can be employed for connecting the seat to the vehicle frame.

Inertial simulators represent a potential mean for testing and improving the design of seats with mechanical dampers. A parallel manipulator, e.g. the one shown in Figure 1, can be used to simulate the high accelerations produced by the blast pressure consequent to the explosion of 3-4 kg TNT mine. The prototype of the seat can be placed on the upper platform of the simulator, either with a dummy or a human person seated on it. Experiments may be conducted on dummies by reproducing acceleration fields of the same magnitude of real ones. Moreover reduced acceleration fields can be replicated on human operators seated on the experimental mock-up, in order to carry out a medical assessment of the system, by evaluating the injury potential to the human body. The results of the medical protocol conducted on the human body can be extrapolated, in terms of induced injury, to the case of higher acceleration vector fields.

Conceptually the rendering to the human operator of the sensation of a physical interaction with a virtual environment can be achieved by utilizing appropriate interfaces capable of generating adequate sensory stimuli to the operator. Such interfaces, called Haptic Interfaces (HIs), are force feedback devices that can exert a controlled force on the operator’s limb as if he was touching a real object.

HIs can greatly enhance the realism and the sensation of immersion perceived by the operator in the Virtual Environment, while using CAD tools for the design/assessment of new products.

The most important characteristics that an HI must fulfill are high backdrivability, low inertia (related with the transparency during the motion of the device), absence of mechanical plays, mechanical stiffness greater than 5 N/mm, isotropic force response in the workspace (necessary to avoid vibrations and penetration into virtual objects). The low-level control system needs to run with a frequency up to 1KHz and to maintain the coherence with the graphics representation of the simulation.

HIs, can be usefully employed for the simulation of virtual assembly and maintenance procedures, with the aim of studying the feasibility of some particular mounting operations in mechanical assemblies and verifying the level of operator’s tiredness induced by the task.

In particular in order to evaluate the execution of such procedures in complex mechanical assemblies, it is necessary to use HIs with a workspace close to the real one of the human arm and with multiple contact points on the operator’s arm. Force feedback anthropomorphic arm exoskeletons, which can be worn by the operator in a natural way with a reduced encumbrance, are the ideal candidate solutions for the simulation of such complex tasks.

The possibility of exerting contact forces on different points of the operator’s arm allows assessing the feasibility of mounting procedures in huge assemblies. For instance it would be possible to evaluate the reachability of a screwed hole in a motor housing by the operator’s arm holding a wrench and to find the interference with other parts along the wrench path.

This paper describes two different Haptic Interface systems, which can be employed for the execution of operations of virtual prototyping. The underlying issues related both to the control and the design of such systems are also presented.

2 Characteristics of Haptic Interface systems

Some basic features of Haptic Interface systems can play a relevant role in the execution of Virtual Prototyping operations:

- Number of Points of contact: Haptic Interfaces providing multiple point of contact allow an enrichment of the experience in the virtual environment. Both the time necessary to identify the shape of an object in a virtual environment and the adopted exploratory procedure are directly correlated to this number [10]. Exoskeletons systems generally allow replicating multiple points of contact. In Virtual Prototyping applications this provides the possibility of simulating operations such as assembling and maintenance, by taking into account also the encumbrance of the operator’s arm during the execution of operations.

- Grounded vs. Portable Haptic Interfaces. Portable Haptic Interfaces allow the operator to perform a free motion and to touch virtual objects within a large workspace. Grounded Haptic Interfaces have the main advantage of being generally characterized by a reduced encumbrance, which allows to locate them on a desktop, while, as a drawback, the reachable workspace is reduced.

- Capability of replicating torques: Capability of replicating torques is important when operations of assembling have to be replicated. Typically in the case of inserting a peg in the hole, the reaction torques generated by the misalignment of hole/peg axes provide the indication of correct fitting to the operator.

- Mechanical properties of Haptic Interfaces: Haptic Interfaces are traditionally designed according to the following general guidelines: low moving masses and inertia, low friction, high back-drivability, adoption of smooth, low play transmission systems, high structural stiffness, high force and position bandwidth. The fulfillment of such requirements is generally achieved by the adoption of tendon transmissions for remote actuation together with grounding of motors.

3 The arm force exoskeleton

The PERCRO arm force exoskeleton [7] (see Figure 2) is a 7 degrees of freedom (DOF) HI, tendon actuated with DC brushed motors. The system can be configured with 5 DOF only, with a handle or a glove fixed to its last link. The kinematics of the first 5 DOF of the system is shown in Figure 3.

The exoskeleton is equipped with optical encoders at each joint and three force sensors, based on a strain gauge architecture that can measure the torque on the last three joints of the system.

Figure 2 The arm force feedback exoskeleton

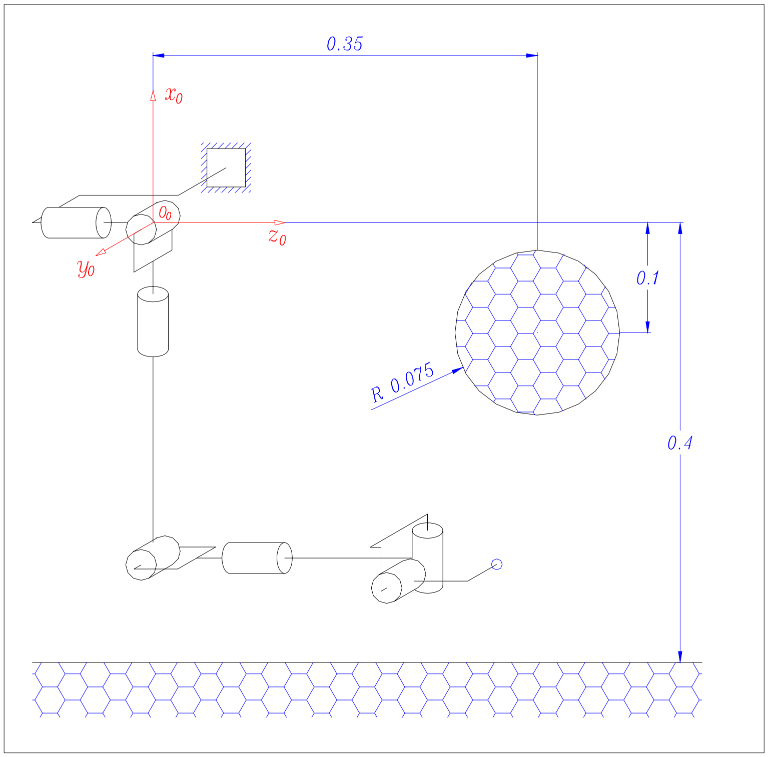

Figure 3 The virtual environment and the Arm-Exoskeleton worn by the operator in the 5DOF set-up

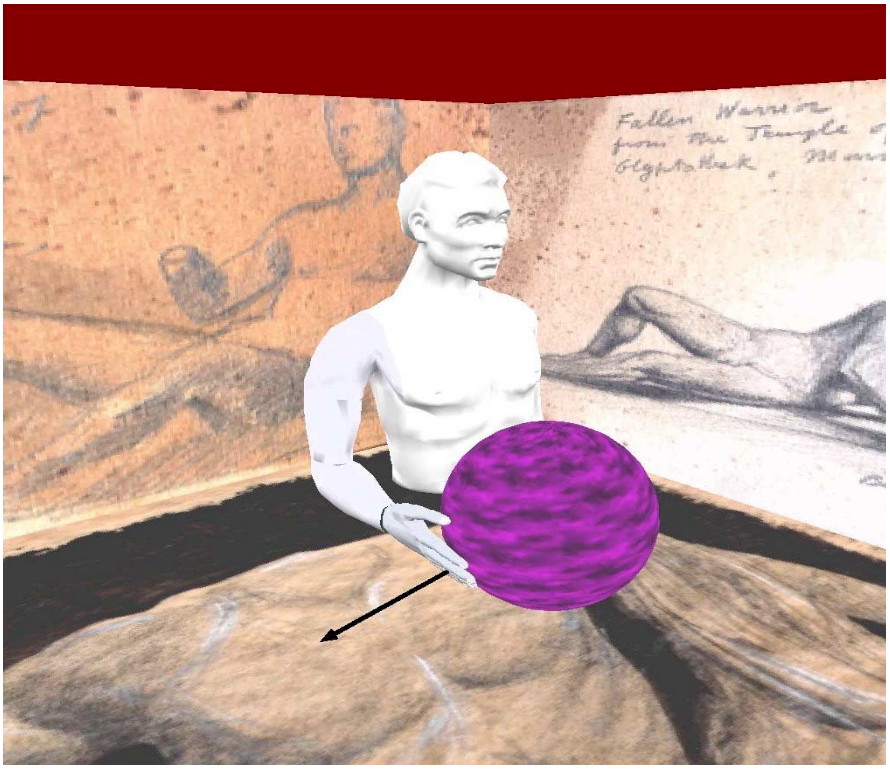

Figure 4 Representation of the contact in the Virtual Environment

In the following the results of some haptic experiments that have been conducted on the arm exoskeleton are presented.

In the Virtual Environment a full-body avatar of the operator is represented as it is shown in Figure 4, while the contact forces are displayed as solid arrows. The operator can observe the movements of his arm on a wide screen, on which all the computer generated Virtual Environment is projected. Several objects with different geometrical shapes have been represented, such as a sphere, a wall, a cube and polyhedral objects, according to the scheme illustrated in Figure 3. The operator can move freely his arm in the space, without feeling the weight of the exoskeleton, since gravity and friction forces are compensated by the action of motors.

A measure of forces and displacements of the contact point during the simulation allows to assess the performance of the system, i.e. the capability of providing the correct perception of the contact to the user.

When the hand enters in contact with an object, forces are generated against the operator’s hand in order to impede it to penetrate in the object.

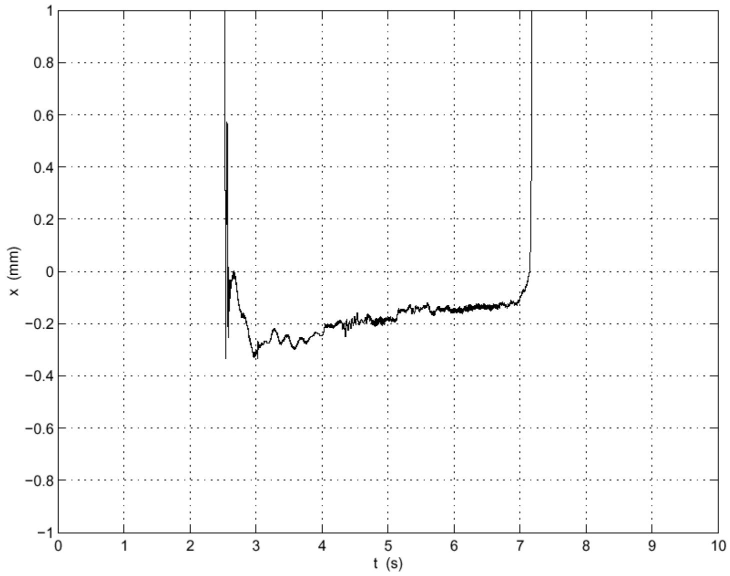

Figure 5 Plot of position vs. time during the simulation of the contact with a virtual wall at x=-0.2 mm

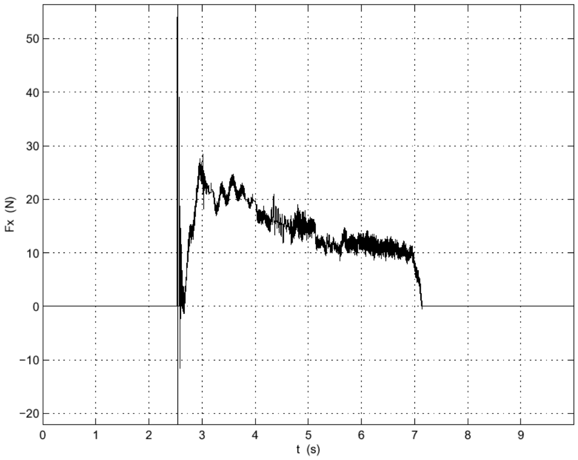

Figure 6 Plot of force vs. time during the simulation of the contact with a virtual wall at x=-0.2 mm

Figure 5 and Figure 6 respectively show experimentally measured position and force during the contact between the operator's hand and a virtual wall. The haptic cues are displayed to the operator by simulating virtual mechanical impedance at the contact point. The calibration studies of the controller have permitted to set up the optimum value of the impedance, in order to avoid the onset of vibrations or the sensation of a very soft surface. As it can be observed in the plots, after a transient peak due to the collision with the surface, the reaction force reaches a stable value of about 15 N.

The optimum parameters of the simulated mechanical impedance that determine the best performance during the contact have been estimated as a mechanical stiffness of 80 N/mm and a viscous damping of 0.3 N/(s·mm).

Anthropomorphic force-feedback exoskeletons can be suitably employed in Virtual Prototyping applications, where a full immersion of the operator can be realized by wearing such devices in a natural and comfortable way.

In order to extend the capability of PERCRO arm exoskeleton system, a portable device for the hand has been recently designed at PERCRO for the force-feedback on user's fingertips during grasping.
Such a device will be worn by user's forearm and integrated with the arm exoskeleton on its terminal link that will support its weight. While the micro-system will allow enhancing the stiffness and the perceived inertia of the systems where a manipulation task is performed with the fingers, the macro system will allow reaching a greater workspace with the hand.

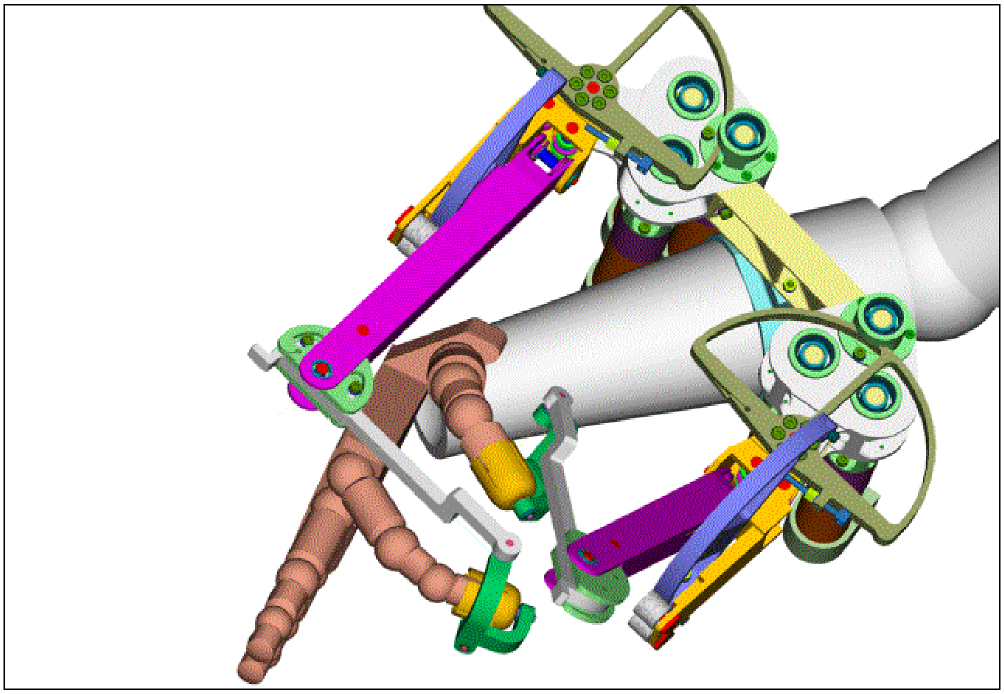

Figure 7 The pinching haptic interface

Such a system will allow the simulation of grasping and moving objects in the space, with the correct feeling of interaction forces/torques generated by the contact with other objects.

4 The Desktop Haptic Interface system

Another paradigm of interaction with a virtual environment can be realized with desktop HIs. HIs with reduced number of degree of freedom can be employed for the three-dimensional exploration and navigation in the Virtual Environment enriched with the sensation of contact with the virtual objects. Low DOF HIs represent an alternative choice, when it is not requested to sense the posture of the entire human arm and the nature of the performed task can be carried out with a single contact point.

An example of such a device is the desktop two Haptic Interface system realized at PERCRO, shown in Figure 8. Such a 2 DOF HI [5] is actuated by a novel transmission system, which allows increasing the isotropic behavior of the system force response. The HI can exert forces up to 10 N in its plane. Although the system possesses a plane geometry, it can be used for rendering 3-dimensional shapes too, by exploiting vector fields of lateral forces: a force resistant to the motion of the operator's hand and lying in the plane of motion is perceived as a positive slope, while a force pushing along the motion direction as a negative slope. This effect has been exploited in numerous investigations [11] to display virtual features, such as holes or bumps. The main advantage of a desktop device is the reduced cost with respect to higher DOF HIs.

Figure 8 The desktop 2 DOF HI

The system is controlled in real-time through a control system based on two main treads running with different clocks, according to the architecture shown in Figure 9. Two different nodes manage the execution of the two threads. The Haptic Module is executed on a DSpace Control Board, while the Graphics Module is executed on a Pentium III 1GHz equipped with NVidia GetForce3 Graphics Card.

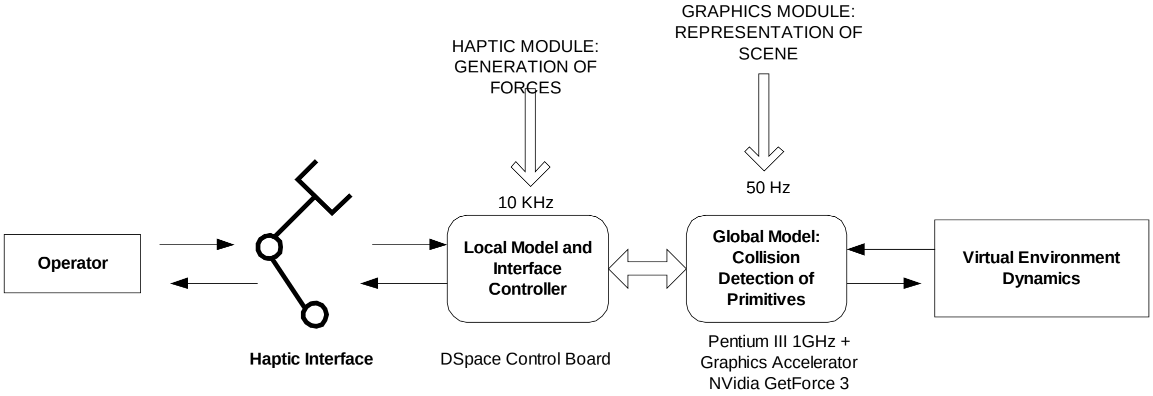

Figure 9 Block representation of system architecture

The thread that manages the graphic representation of the overall virtual environment is executed at each 30 msec and, detects primitives that are in contact each other in the Virtual Environments by means of a collision detection algorithm.

In the case of the planar kinematics, it has been adopted a collision detection algorithm based on the generation of Voronoi diagrams and distance fields of colliding primitives using graphics hardware. Such an algorithm, developed for Computer Graphics purpose only [8], has been integrated with a hierarchical collision detection algorithm and adapted in order to fulfill the requirements of force feedback generation.

Figure 10 shows the concept underlying the collision detection algorithm in a simple case of contact between a point and a circle, represented by means of polygonal representation. When the point is closed to the circle, Voronoi diagrams are computed in a square area surrounding the point. Such an area is divided in sub-areas with different colors, each different color identifying the polygon edge that is closest to the point.

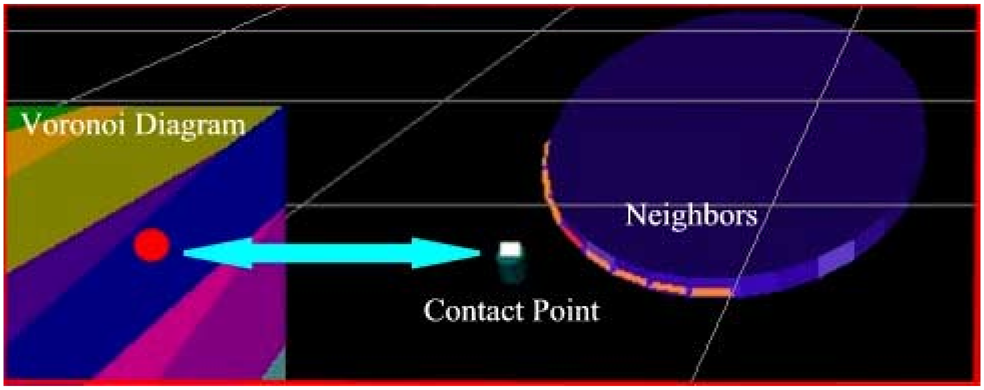

Figure 10 Example of Voronoi Diagram associated to the contact of point with a circle

On the basis of the contact primitives, a local model of the virtual environment is extracted by selecting neighbors of the primitives that are in proximity of the contact point. Such local model is then sent to the Haptic Module, which generates the force feedback at a refresh rate of 10 KHz. The Haptic Module is based on a Fast Collision Algorithms incorporating a God-Object for the computation of forces, according to [9].

Figures 10,11,12 show a sequence of different frames of a virtual simulation of insertion of peg in the hole. When the peg is pushed against a boundary of the yellow housing, a reaction force is computed in real time, which avoids the penetration of the two bodies.

The peg in the hole represents a paradigm of assembling operations. In such a case the contact forces allow to feel whether the correct relative position of the two bodies has been addressed for the insertion task.

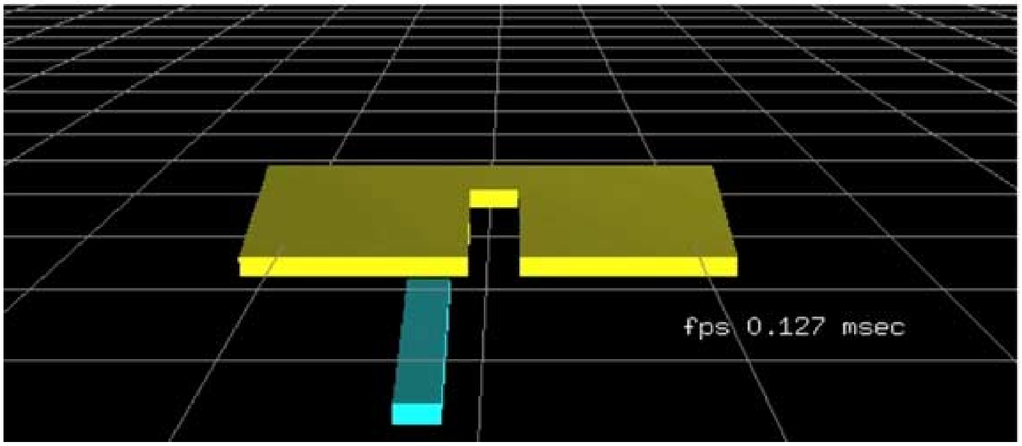

Figure 11 Peg in the Hole task: non colliding objects

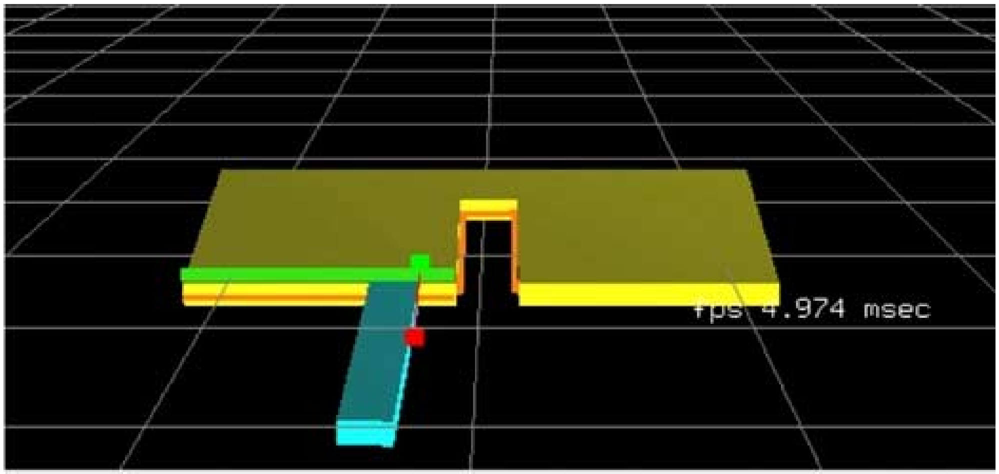

Figure 12 Peg in the Hole Task: The peg is colliding with an edge of the yellow housing

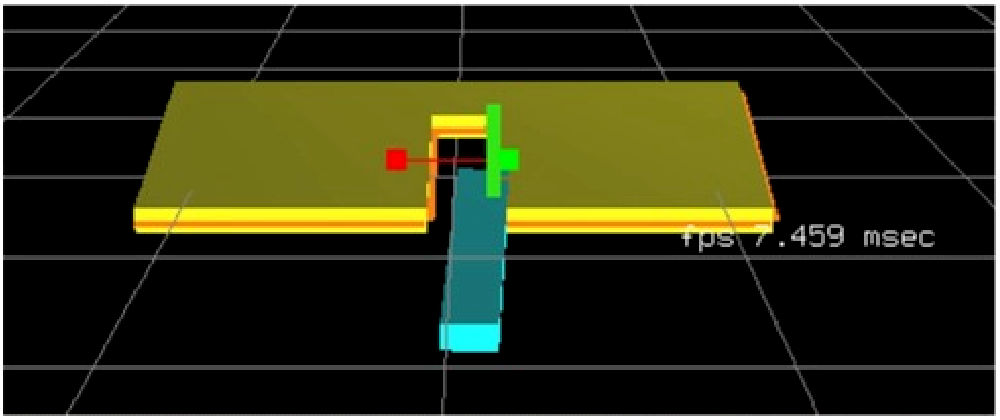

Figure 13 Peg in the Hole task: The peg is colliding with an edge inside the hole

5 Conclusions

Haptic Interface systems present a great potential for applications in virtual prototyping. Although multi-degree of freedom systems are preferable for complexity of tasks that can be simulated, low degree of freedom haptic interfaces could constitute a valid alternative, in term of cost and encumbrance of device.

During the design phase of military vehicles, inertial motion simulators can be suitable employed for the assessment of protection/safety adds-on, e.g mechanically damped seats for the reduction of potential injury to the occupants, both from a technical and medical perspective.

Beyond the assessment of occupant safety in case of mine detonation under armoured vehicles, another issue worth of investigation is the assessment of the stress conditions, which a pilot of fighting aircraft is subjected to during flight. As a concluding remark, the usage of HIs is a meaningful tool for the design of military vehicles that allows great economy of time and money, especially when it is requested to assess the relation between human and machine under extreme conditions of work.

Reference

[1] Niesen MR, Luecke GR, *Virtual Dynamic Prototyping for Operator Interface Design* Proc, of IEEE RO-MAN99, Pisa-Italy.

[2] Yoshikawa T, Yoshimoto K, *Haptic Simulation of assembly operation in Virtual Environment,* Proc. of ASME IMECE 2000, Symposium on Haptic Interfaces and Teleoperation, Orlando FL-US.

[3] Lu SC-Y, Shpitalni M, Gadh Rajit, *Virtual and Augmented Reality Technologies for Product Realization*, Annals of the CIRP Vol. 48/2/1999.

[4] Frisoli A, Avizzano CA, Bergamasco M, Data S, Santi C, "Dynamic modeling of primary commands for a car simulator", IEEE 2001 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM '01) 8–12 July 2001 Como, Italy.

[5] G.M.Prisco, A.Frisoli, F.Salsedo, M.Bergamasco,"A novel tendon driven 5-bar linkage with large isotropic workspace", Proc. of ASME (American Society of Mechanical Engineers) IMECE99, International Mechanical Engineering Congress and Exposition (http://www.eng2.uconn.edu/alarm/imece99), Nashville (TN-USA).

[6] D Ferrazzin, F Salsedo, A Frisoli, M Bergamasco, "Strategy Manager Implementation in a Motion Based Two-Wheeled Vehicle Simulator", 32nd ISATA, International Synposium of Automative Technology and Automation, Vienna-Austria.

[7] Bergamasco M, *Force replication to the Human Operator: The Development of Arm and Hand exoskeletons as Haptic Interfaces*, Proc. of 7th International Symposium of Robotic Research 1995, Springer Verlag.

[8] Hoff KE, Culver T, Keyser J, Lin M, Manosha D, *Fast Computation of Generalized Voronoi Diagrams Using graphics hardware,* SIGGRAPH '99

[9] Craig Zilles and Ken Salisbury, *A Constraint-based God-object Method For Haptic Display*, IROS '95.

[10] G Jansson, *Basis Issues concerning visually impaired people's use of haptic displays*, Proceedings 2000 Intl COnf Disability, Virtual Reality \& Assoc. Tech.

[11] J. M. Weisenberger, M. J. Krier, M. A. Rinker ,*"Judging the Orientation of Sinusoidal and Square-Wave Virtual Gratings Presented via 2-DOF and 3-DOF Haptic Interfaces,"*, Vol. 1, No. 4, March, 28, 2000