Interactive Virtual Prototypes for Testing the Interaction with new Products

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ABSTRACT

Today, the tests of a new product in its conceptual and design stage can be performed by using digital models owning various levels of complexity. The level of complexity depends on the nature and on the accuracy of the tests that have to be performed. Besides, the tests can involve or not the interaction with humans. Particularly, this second aspect must be taken into account when developing the simulation model. In fact, this introduces a different kind of complexity with respect to simulations where humans are not involved. Simulation models used for numerical analyses of the behavior of the product (such as Finite Element Analysis, multi-body analysis, etc.) are typically named Digital Mock-Ups. Instead, simulations that are interactive in their nature, requiring humans-in-the-loop, are named interactive Virtual Prototypes. They cannot be intended as a simple upgrade of a CAD model of a product, but they are instead a combination of functional models, mapped into sensorial terms and then accessed through multisensory and multimodal interfaces. In this paper, the validity of this concept is demonstrated through some case studies where interactive Virtual Prototypes are used to substitute the corresponding physical ones during activities concerning the product conceptualization and design.

Keywords: virtual prototyping, mixed prototyping, CAD modeling, simulations.
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1 INTRODUCTION

Simulation and testing in the Product Development Process (PDP) are important activities necessary to validate or discard the decisions taken by designers during the process [1]. Usually they are performed on prototypes that simulate at best the aspect of the product that has to be analyzed and tested. Simulations can be performed at different steps of the process and with a different level of complexity. As a consequence prototypes can be variably complex and similar to the final product. For example, simulations about engineering performances, such as structural, dynamics or fluid dynamics analyses, can be nowadays performed on digital models, named Digital Mock-Ups (DMU), but also using physical mockups. Tests based on DMU are less expensive than the latter but generally less accurate.

During the PDP there is also the necessity to perform some tests including the direct human interaction with the product. There are two ways they can be performed: the first is by using physical mockups tested by real humans, or alternatively by using digital mockups and virtual humans. Tests based on physical prototypes are expensive because of the cost of the prototype, and are not enough flexible, since changes on a physical prototype are difficult to perform. Tests performed using both digital models of products and humans are based on the simulation and simplification of the human behavior. Because of the simplification, the simulation is not so precise as that performed by a real human. Beside these two alternatives, Virtual Reality (VR) offers the techniques and technologies that can enable us to run tests based on human interaction with the product by using digital prototypes, accessed by real humans through multimodal and multisensory input/output interfaces. Digital prototypes can be the combination of any kind of functional, multi-physics and multi-domain models, and require to be translated into sensorial terms in order to be accessed by humans. These kinds of simulation models are hereafter named *interactive Virtual Prototypes*.

Beside the evolution of the human-computer interfaces that enable us to interact naturally with digital information, there is another important aspect to take into account. In the last four decades the use of CAD tools in the Product Development Process (PDP) has grown progressively and nowadays it covers quite completely all the steps of the process: from the initial concept down to the production planning [1, 2]. With CAD tools, the design of a new product usually starts with the geometrical modeling. These geometries are progressively enriched with information and become then the basis for any kind of analysis. Geometries for example are used as the starting point for engineering finite element analysis, both structural and fluid-dynamic. The evolution of the commercial CAD tools, which include all kinds of analyses as an add-on of the geometrical modeling environment, seems to clearly show this approach. Geometry is the core of the design activity. But this is atypical in the way of thinking of the engineering world where usually a problem is solved by means of simplified functional models. It seems that with the use of CAD tools designers think at the product as being shape-driven instead of function-driven. The designer/engineer creates the final target shape since the beginning and then he performs all the analyses, including the functional analysis.

While for purely numerical analyses, such as structural and fluid-dynamic, this approach may give valid and good results, this is not always true for tests involving humans. In this case the attempt to extract all the information to convey to the human sensorial/perceptual system from geometries is an inappropriate approach. This is due to the fact that interacting with human senses requires real time feedback, and the calculations based only from geometries are still too slow to grant the real time. If we change the way of thinking from a geometry-driven approach to the functional-driven one, the extraction of information about human-product interaction would be straightforward.

In the paper we propose an evolution of Virtual Prototypes, where the geometry is not used for computing all the information sent to the human sensorial/perceptual system but instead is solely used for visualization purposes. The Virtual Prototype is defined as a net of interconnected functional, multi-physics and multi domain models. When these models are translated into sensorial models that can be accessed by means of multimodal interfaces, the Virtual Prototype becomes *interactive*. The result of the conversion of a Virtual Prototype into multisensory functional models consists of an *interactive Virtual Prototype*. There is always a correspondence between the original Virtual Prototype

(VP) and the interactive Virtual Prototype (iVP). And this is reflected by the fact that while testing a VP through the interaction with its corresponding iVP, whenever users ask to make some changes on it, these are mapped back into the VP.

In the paper we describe this concept through some case studies where interactive Virtual Prototypes are used to design and test the interactive aspects of consumer products. The paper is structured as follows: first we report the main achievements in the field of CAD modeling, Engineering Simulation and Virtual Prototyping. Then we give a definition of interactive Virtual Prototype, and we describe the case studies. Finally we draw some conclusions.

2 STATE OF THE ART

Since the initial studies on two-dimensional drafting systems at the beginning of the 60s [3] up to the three-dimensional and parametric evolutions of the 90s [2, 4], Computer Aided Design (CAD) tools have been introduced successfully in several steps of the Product Development Process. Currently they are used as a support for designers to communicate and test their ideas from the initial concept phase up to the Management of the Product Lifecycle [1]. The core of CAD tools is the geometrical modeling environment and all the simulations and testing activities are based on enriching the geometry with additional information. The geometrical modeling environment is used to generate the “nominal” geometric model of the product with the strong constraint of being fully and only geometrical. This means that there is not information about features like deformability, tolerances, roughness, and physical properties in general. Consequently there is not the possibility to simulate all the physical and real processes connected and derived by the real product behavior during its functioning, which are usually at the origin of all engineering issues and problems to solve. Certainly the shape (and the geometric abstraction) is the starting point for creating functional models representing local or global physical phenomena in a separate way (i.e., stress, strain, deformations, vibrations, noise, wear, change of physical properties, etc.). This can only be done through an interactive generation of detailed and dedicated models done by the engineer. Of course, all these local problems have to be solved in the phase of embodiment or detailed design, but are only small issues within the context of the simulation of the global behavior of a product, especially for what concerns the behavior perceived by the user.

The interaction with the CAD geometries for modeling and testing purposes is still mediated by traditional I/O devices, e.g. mouse, keyboard and 2D displays. Virtual humans have been introduced within the CAD environment as a means to simulate the human behavior and the human interaction with virtual products [5].

In the last two decades we have assisted to an evolution of Virtual and Augmented Reality technologies that have suggested the possibility to interact with digital information and even to perform testing activities by putting the real human in the interaction loop [6]. This is feasible by allowing the human to interact with the digital model through a multimodal and multisensory environment by enabling the same sensorial channels that are used during the interaction with the real object. Technologies for the sense of vision have reached in years a high qualitative level, so that they allow a photorealistic and real-time rendering of visual information. This evolution has been driven by the consistent research concerning the sense of vision. Also regarding the sense of hearing the technologies are sufficiently evolved so as to guarantee a high fidelity rendering of sound information [7].

The same thing has not happened for the senses of touch, smell and taste, which in years have been studied less than visualization and hearing. Technologies for touch are still divided in two major categories: force-feedback devices that return to the user forces and torques (a review can be found in [8]), and tactile displays that communicate through the skin [9]. At the beginning of the 90s the first commercially available Phantom devices have appeared [10]. In the very recent years the haptic community has seen a significant increment of researchers working on this topic, so that we can imagine that the haptic interfaces will reach a high quality level in few years.

The consequence of the increased availability of visualization technologies with respect to those for touch is that for years the testing activities performed on Virtual Prototypes has been limited to visualization aspects, such as aesthetic appreciation, choice and evaluation of different aesthetic alternatives and so on. What for years have been called Virtual Prototypes are actually Visual Prototypes, where the interaction has been confined to pure visualization aspects. It is straightforward that with the evolution of Virtual and Augmented Reality interaction techniques and technologies, and the introduction and major availability of technologies for the sense of touch and hearing, the user interaction can be much more complex and rich, so that the number and the kind of testing activities can be enlarged to those involving a more complex interaction. Another interesting aspect is that Virtual Prototypes can represent the whole product or simply a part of it by adding digital information to physical objects and environments. These prototypes are called Mixed Prototypes, as Virtual Reality becomes Mixed Reality when real and virtual information is mixed [11].

In years the term "Virtual Prototype" has been used to identify any kind of digital model that is used as a substitute of a real prototype to perform testing activity of different nature; from pure numerical analyses, such as stress analysis, to those requiring the human-in-the-loop, such as ergonomics analyses performed by real humans [12]. In this paper we aim at giving a clear distinction between the Virtual Prototype that is the combination of functional models of different kind of domains and the interactive Virtual Prototype that is a translation of these models into sensorial terms accessed through multisensory and multimodal interfaces. In the following we will provide with the definition of interactive Virtual Prototype and the concept will be demonstrated through some case studies.

3 VIRTUAL PROTOTYPE AND INTERACTIVE VIRTUAL PROTOTYPE

In this section we propose a definition of Virtual Prototype (VP) and of interactive Virtual Prototype (iVP), focusing on their role and use in the Product Development Process. In general, a prototype is built for testing purposes and is specifically oriented to a goal. Therefore, there can be many prototypes, one for each use and purpose. We can define the ideal virtual prototype as a network of single or multiple domain functional models, which fully represent the physical behavior and internal interactions. The models simulate all the phenomena concerning the functioning of the product in the various contexts of its life. This definition of Virtual Prototype is only ideal, and in fact in reality we use a multitude of specialized Virtual Prototypes, which are oriented to limited goals.

3.1 Requirements for the interactive Virtual Prototype

A Virtual Prototype is intended as the digital substitute of a physical prototype used for different testing activities during the Product Development Process [12, 13]. As is the case for physical prototypes, we do not expect that the Virtual Prototype reproduces the full behavior of the final product, but it should behave like it only for those aspects that we are interested to test and validate.

As a consequence the Virtual Prototype can be:

- *Based on functional model for each technical domain.* In order to behave and react like a real product the Virtual Prototype should be based on a functional model that characterizes and simulates the domain (or the domains) of the real product to evaluate and test. Nowadays, multi-domain simulation tools and physics-based algorithms allow the integration of multiple and interacting simulations. The results returned by these simulations can be very accurate and reliable. The main limitations of the physics-based algorithms and the multi-domain simulation environments are that they might not easily work in real-time if the tests require the human-in-the-loop.

- *Sharable among different stakeholders.* One interesting advantage of using virtual prototypes is that they can be shared over the network and accessed by different stakeholders at the same time. This enables collaborative design and testing activities [14].
- *Modifiable and parametric.* One of the most important advantages of Virtual Prototypes is that they are easily modifiable and can be even parametric. By using the physical prototype of an object, a person can only express an opinion as to whether he likes or dislikes it, but cannot easily test variants of the object. By using a parametric virtual model instead the user can ask to make changes of the prototype until an optimum has been reached. It is clear that in the case of using Mixed Prototypes only some parts can be modified, i.e., the virtual component.
- *Context sensitive.* The prototype should reflect the changes due to the context it is put in. Especially for Mixed Prototypes, information from the real world should be captured and projected into the virtual one.

When the Virtual Prototype has to be used for testing activities involving direct human interaction, it becomes an interactive Virtual Prototype (iVP), which should meet different requirements:

- *Realism.* The iVP should react at human senses exactly as a physical prototype, hiding to the user the complexity of the simulations, and of the technologies at its basis. When the technologies, both hardware and software, are not able to reproduce all the information in a realistic way, a Mixed Prototyping approach should be preferred [11].
- *Real-time feedback.* The iVP should react to user's actions in real-time (from the users' perception point of view), with no perceivable delays (this impacts even on the realism of the simulation). It means that simulation algorithms should be fast enough to grant a real-time feedback. In case this is not feasible, simplified algorithms should be used. Simplifications should anyway grant the quality of the perception of the object. This implies that the problem moves from the simulation of the ideal physics-based behavior, to the simulation of the faithfully perceived physics-based behavior. It is highlighted that the most important aspect of the interactive Virtual Prototype is no more the complexity of the simulation of the product, but how the results of the overall simulation is perceived by the humans.
- *Multimodality and multisensory.* The iVP should involve the same sensorial channels and the same interaction modalities that are involved during the interaction with the real product. Since involving several senses means using dedicated devices for each sense, it has to be taken into account that perception might be affected by the device if it is not transparent, and that the sense of presence [15, 16] might decrease if the user does not feel to be into the virtual world because of the many and invasive devices worn.
- iVP should be based on:
    - *different functional models for each sense.* Each sense should be treated separately from the other ones. This would allow us to simulate situations that are not possible with physical prototypes (for example, sounds not resulting from the exertion of specific forces on an object).

- o *different functional models for each external behavior to analyse and test.* The interactive Virtual Prototype to use for specific and distinct analyses, for example for the ergonomic analysis, should be based on different functional models from that used for the emotional response analysis.

- *Parametric for each sense.* The functional model implemented for each sense should be modifiable until an optimum has been reached. The easiest way is to make the model parametric.
- *Sharable among different users located around the world.* Sometimes testing activities on the same product should be performed in different cultural context. interactive Virtual Prototypes might be used for this kind of testing activities.

3.2 From Virtual Prototype to interactive Virtual Prototype

The differences, described so far, between the Virtual Prototype and the interactive Virtual Prototype are schematically represented in Fig. 1 and discussed in the following.

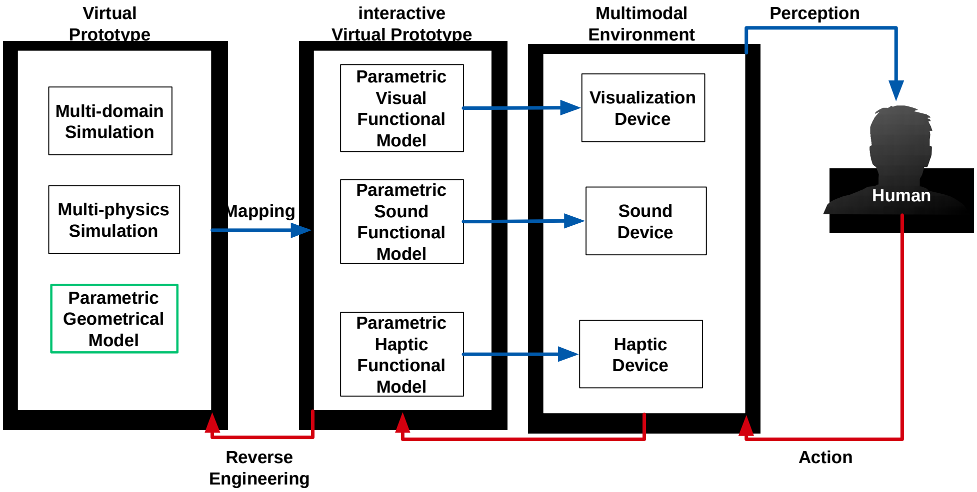

Fig. 1: The interactive Virtual Prototype is a combination of functional sensorial models accessed by means of a multimodal and multisensory input/output interaction environment. The Virtual Prototype is a combination of functional models for each technical and physical domain.

A Virtual Prototype is the combination of geometrical models, and multi-physics and multi-domain simulations. When it is mapped into sensorial terms, which can be accessed by the humans by means of multimodal and multisensory interfaces, it becomes an interactive Virtual Prototype. The user's action is applied on the interactive Virtual Prototype by means of input devices, and produces a sensorial feedback that is returned to the user though the output interfaces. Clearly what the human perceives as realistic, and what reacts in real-time is not the Virtual Prototype but is instead its mapping into sensorial terms. And when the user asks for a change of one of the product feature, he is actually asking for a change in the perception of the prototype. This is feasible only if the functional models are parametric, for each sense. When the testing session is completed, the sensorial prototype should be mapped back into design specifications. This step corresponds to the phase called reverse engineering in the figure.

The testing activity based on the use of interactive Virtual Prototypes can be imagined as composed by two main loops (as represented in Fig. 2): the first one, named Interaction Loop which requires a simulation model that runs around the human's perceptual specification in terms of refresh rate and where even modifications on the parametric sensorial models should be reflected in real-time. The other loop, named Mapping Loop, may not necessarily work at the same rate of the Interaction Loop, since it is not directly connected with the human. In general the two loops might run separately. When test results are obtained from the Interaction Loop they can be mapped into design specifications through a Reverse Engineering activity that does not run during the Interaction Loop. Even in case a change into the multi domain models is performed it can be mapped into sensorial parametric functional models while the Interaction Loop is not running.

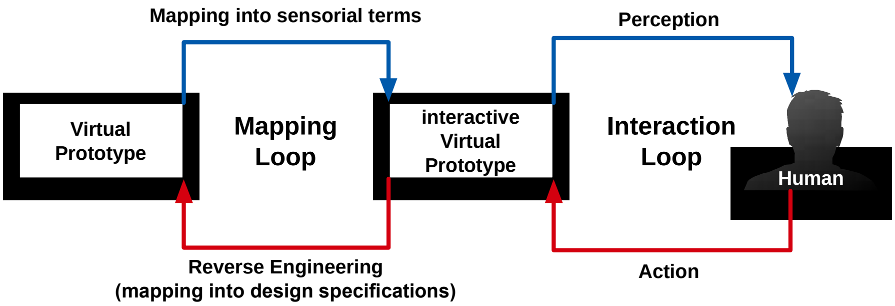

Fig. 2: Testing activity is split in two main loops: the Interaction Loop that represents the continuous action/perception activity of the human with the interactive Virtual Prototype, if modifiable, can be used to capture the optimal behavior, and the Mapping Loop where the optimal sensorial terms are mapped to design specifications.

In a traditional product development flow, the process illustrated in Fig. 1 and 2 should be read from left to right, meaning that after some design choices the multi domain simulation model is built and the resulting iVP tested and finally refined, until an optimum has been obtained. This optimum is then mapped back to the VP. In the hypothesis of a usage-driven design the process should be read from right to left. The multisensory iVP can be created and tested and these results can be used as input for the design of a new product. It is straightforward that while going from left to right allows us to refine existing designs of products, contrariwise going right to left allows us to test new interaction solutions, without any existing design constraints.

In a traditional PDP [1] the prototype to test interactive aspects is usually available at the end of the process. In this way significant changes might not be economically feasible. In our approach the interactive Virtual Prototype can be built very early in the process and tested even in the concept phase in case we intend to use the approach from right to left. In this case the iVP is based on sensorial functional models completely independent from any kind of physics-based functional model. Once the optimal perceived product has been "frozen", the sensorial specifications can be mapped into design specifications.

4 CASE STUDIES

In this Section we describe some case studies where the interactive Virtual Prototypes of consumer industrial products are created after an analysis of corresponding real products in order to allow companies to refine their designs. Another case study where the sensorial functional model is not derived from an existing product but on the observation of other products of the same kind is described. Each iVP has been implemented based on simplified functional models, i.e. through parameterized sensorial functional models, so as to be perceived as the real product and as to be modifiable.

The case studies have in common the multimodal and multisensory interaction environment that is composed by technologies for three senses: vision, sound and touch.

In particular the hardware setup is composed by:

- *a rear-projected wall display Cyviz VIZ3D* (www.cyviz.com) for stereoscopic visualization of the product, which is based on two projectors and linear polarizers mounted first on the projectors and then also worn by the user as lightweight glasses. If compared with HMDs, the user is asked to wear a pair of glasses that interfere less with the task he must accomplish;
- *a 3DOF haptic device MOOG-HapticMaster* (www.moog.com/products/haptics-robotics/) equipped with a specific handle prototyped and screwed to the end effector or as an alternative a Haption Virtuose 6DOF general purpose haptic device (www.haption.com) provided with a generic handle. Both the haptic devices offers a large workspace, covering almost the volume reachable by a human arm;
- *a single speaker* for the sound rendering positioned under the haptic system. Different alternatives have been analyzed and tested during the development of the case studies. We have used headsets that have the disadvantage that need to be worn and a couple of speakers to produce the stereo sound effect. Anyway the tendency in 3D sound rendering is to use a single speaker located in space near the sound source [7] and this is the choice we have adopted to reproduce 3D sound;
- *an optical tracking system by ARTracking* (www.ar-tracking.de) used to calculate the user's point of view position and orientation in real-time and to adapt the image for a natural visual exploration of products.

In [17] we have described the implementation of the iVP of a commercial washing machine provided by the Whirlpool Company (www.whirlpool.com). The physical prototype of the washing machine has been provided by the company together with some CAD models. After the analysis of the real prototype the iVP based on three sensorial models has been implemented. In particular the sounds are recorded from the real washing machine and then they are modified by means of sound filters (compressors, reverbs) in order to obtain different sensations of a more or less robust door/drawer. Forces are modeled by means of simplified algorithms instead of physics-based algorithms, and are made parametric in order to be tuned if the user asks for changes. Snaps of the closing drawer are obtained by means of localized force gradients as well as translational limits by means of hidden blocks colliding with the geometry. Sounds and forces are independent, i.e. different sounds can be associated to the same force. This effect is particularly interesting since, as described in [17] users tend to prefer a more robust sound instead of the real one, even if no specific tests have been performed to statistically demonstrate this correlation. In the simulation the user can interact with moving components of the interface, as the drawer, the door, the buttons and the knob. The user can perceive through vision, hearing and touch the pre-defined effect of the washing machine. Then he can ask for some changes so as to tune the interaction effects, until the desired effects are reached. As described in [18] the iVP parameters captured with this method, which are based solely on perceptual analysis, can be mapped back into design specifications.

Fig. 3 illustrates the iVP of the washing machine. In particular it is represented the haptic functional model for the door and related sounds.

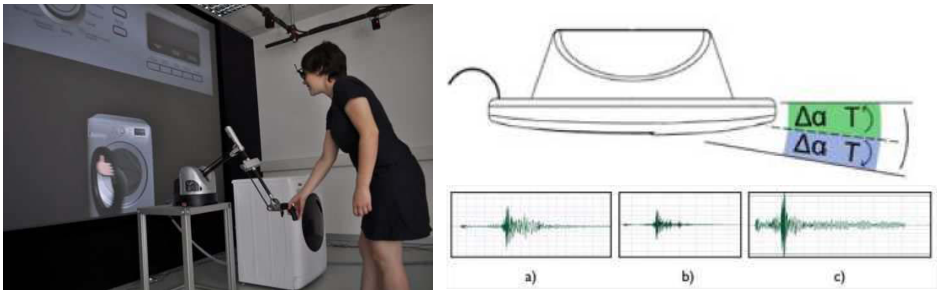

Fig. 3: The interactive Virtual Prototype of a commercial washing machine. The haptic effects for the door are obtained by means of a simplified sensorial haptic model. Sounds are obtained by modifying the original recordings by means of sound filters.

In [18] it is described the implementation of the iVP of a set of hinge mechanisms for household cupboards (illustrated in Fig. 4 on the left). In particular it is described how the haptic effect of three different hinge systems can be obtained by modifying the same haptic model. Even in this case the iVP is the result of the observation and the analysis of the real product, provided by SALICE (www.salice.com). After the analysis a parametric haptic model is created and the hinge systems can be refined based on user tests. Both the two case studies so far described make use of the 6DOF Virtuose Haptic device, equipped with a generic handle. The haptic feedback is altered by the handle, especially for the haptic rendering of buttons and knobs, as described in [18].

In [19] the analysis of a commercial fridge provided by the Indesit Company (www.indesitcompany.com) and the subsequent creation of the interactive Virtual Prototype is described. Forces exerted on user's hand by the product are captured by means of measuring instruments, such as load cells and tracking systems, and sound are recorded at different speeds. The force model is implemented in a way that there is a correspondence between the haptic primitives and the mechanical elements of the real door, i.e. a real spring is implemented through a haptic spring, etc. Regarding the sounds, a psychophysical approach is used to reduce the number of sounds that are necessary to populate a database of sounds connected to different speeds. Different sounds are played only when they are perceptively different [19]. While in the example of the washing machine the user interacts haptically through a general- purpose handle, and this is perceived by the users as a limitation, in this case study a custom handle, which has exactly the shape of the final handle, is prototyped and attached to the end effector of the haptic device. Fig. 4 illustrates the iVPs of the fridge.

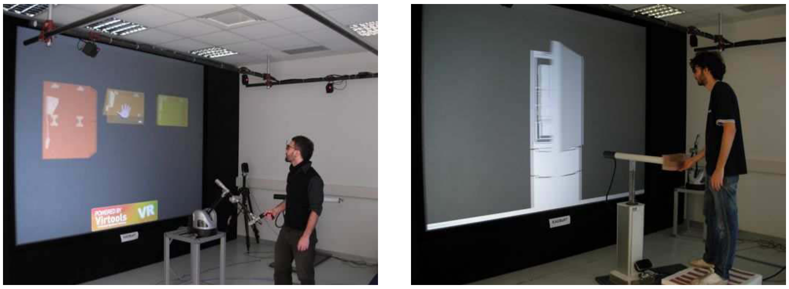

Fig. 4: Virtual Prototype of a set of cupboard hinges (left) and iVP of a commercial fridge (right). In this case in order to increment the realism of the haptic feedback, a custom prototyped handle is attached to the end effector of the haptic device.

Finally Fig. 5 illustrates the iVP of a pulley machine. In this case, differently from the other case studies the aim of the iVP is not to refine an existing design, but instead to experiment on new design concepts. The iVP in this case has been developed based on the observation of the working principles of other existing pulley machines and this behavior has been adapted to a new design. In this case the user is able to test the ergonomics of the new design of the pulley machine and to ask for some changes that can be performed easily before a detailed design is performed. As in the previous case study in order to improve the realism of the simulation the generic end effector of the haptic device has been substituted with a custom shape.

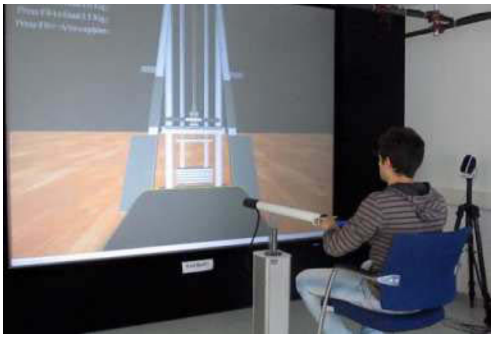

Fig. 5: The iVP of a pulley machine has been implemented from the analysis of other existing pulley machines in order to test design variants and run ergonomic analyses.

5 DISCUSSION AND CONCLUSIONS

The paper proposes a new definition of Virtual Prototyping, which is based on the distinction of product geometry and simulation from the functional models used for the user interaction. We propose a new concept of interactive Virtual Prototype which is a combination of functional models, mapped into sensorial terms and then accessed through multimodal and multisensory interfaces by a user. Interactive Virtual Prototypes can be effectively used in the conceptualization phase of products that involve a use by people, where designers need to test with final users the proposed design solutions, before progressing with the embodiment and detail design. Anyway they can even be used to refine existing designs, or to start new product designs from the analysis and optimization of existing products, as is common in some companies design practice. The paper includes some examples of the implementation of interactive Virtual Prototypes. It focuses on how the models for each sense have been treated separately in order to allow us to test solutions not feasible with physical prototypes. Some of them are implemented on the basis of the analysis of existing products, while some others are pure concepts that can be used as the input for the design activity. While in the research activity described in the paper we have concentrated on the creation of the sensorial functional models, so of the interactive Virtual Prototype, current research activities are focusing on the mapping of the optimal sensorial terms into design specifications, of what we have defined as Reverse Engineering.

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