A Method for Designing Users' Experience with Industrial Products based on a Multimodal Environment and Mixed Prototypes

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ABSTRACT

The paper describes a methodology that can be employed to perform the analysis of aspects related to human interaction with consumer products during the Product Development Process, thanks to the use of mixed prototypes. The methodology aims at helping designers to take decisions earlier compared to the current practice based on not easily modifiable physical prototypes. Authorsõ method considers the interaction with adaptable mixed prototypes as a possible validating procedure for product interaction-enabling features: a multimodal environment is created to perform these validations, integrating three sensorial modalities such as vision, hearing and touch. The paper firstly describes the requirements for the creation of the multimodal environment. Then it focuses on the opportunity of using an approach based on mixed prototypes rather than on completely virtual ones: the intent is to increase the level of òrealismó of the simulation by overcoming limitations of actual technologies for the sense of touch. Finally, a case study is discussed, starting from the analysis of a commercial consumer product up to the interaction with the developed Mixed Prototype. The expected benefits for the product development process are highlighted.

Keywords: virtual and mixed prototyping, haptic interaction, product virtualization.
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1 INTRODUCTION

The attention of companies operating in the sector of consumer products about the emotional response and the perceived quality of products has significantly grown in recent years. It is now clear that besides the technological content of the product there is another component, which influences the purchasing decision that is the consumersõ personal perception of the product. That perception is generated when, at the point of sale, consumers look at or interact with the product itself. Indeed when a rich selection of similar products is available, as it happens in the home appliances market, the winner product will be the one able to influence consumers both drawing their attention and matching their expectations. One way to fulfill that purpose is by eliciting a positive emotional response.

For products requiring human interaction, the elicited emotions are correlated with a complex combination of sensorial cues coming through different channels such as touch, vision, hearing and smell [1]. Tests to evaluate the quality of user interaction can be performed throughout the product development process; they typically require the building of several costly and time-consuming physical prototypes, which should work like, feel like and look like designersõ product intent and drawings. The main reason for using physical prototypes is that tests performed on the digital model of the product generally return poor and ineffective results concerning interaction-based aspects.

Virtual Reality offers a set of useful technologies that can be exploited to perform these kinds of tests on Virtual or Mixed Prototypes (V/M Prototypes) instead of on physical ones [2, 3]. The advantage of using V/M Prototypes is mainly related to the fact that they are less expensive than real ones and even highly modifiable, thus enabling designers to perform design review sessions in a more dynamic, fast and efficient way. Virtual technologies help product developers to involve potential users within the optimization loop existing between the product design phase and the testing one allowing a continuous evolution of the V/M Prototype; usersõ test results can be used to rapidly update the initial V/M prototype instead of spending effort on building new physical prototypes as it usually happens following a more traditional approach (Fig. 1).

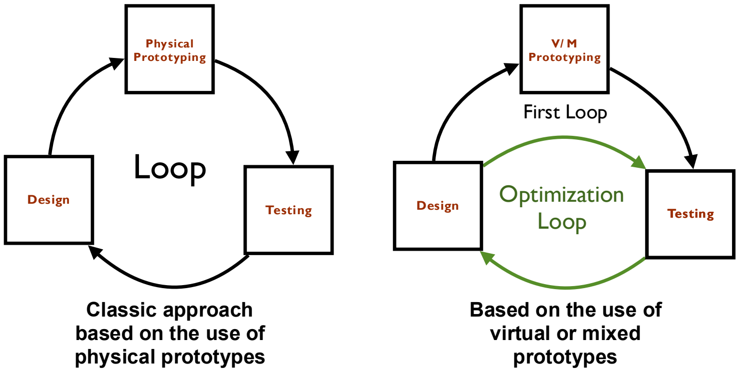

Fig. 1: The use of modifiable V/M Prototype allows us to perform a testing activity without the need of continuously building new prototypes. This fact contributes to reduce the time that is necessary to complete the Product Development Process, and the cost of the overall process.

The validity of the test results depends on how much the V/M Prototype is able to replicate the behavior and the appearance of the new product concept. That ability is strictly connected with the capability and performances of Virtual Reality technologies, both hardware and software: how they are able to render product information in a òrealisticó way represents a key aspect.

Technologies for the visual and the hearing sensorial channels have matured in years; it is now possible to simulate sounds into a virtual environment with a high degree of òrealismó and represent images with a photorealistic quality. That is not completely true for the haptic channel. Even if big effort has been spent by the research community in trying to reproduce touch cues with a high degree of realism, results are not yet comparable with those of sound and vision. Anyway, when the haptic technology is not able to perfectly reproduce force and tactile cues in a òrealisticó way, one can substitute real cues to the simulated ones. That approach allows us to perform testing activities on virtual and mixed prototypes by mixing information for all the three sensorial channels (including touch that plays a fundamental role in human interaction), and by exploiting the available technology.

This practice, if compared with a classic Product Development workflow, can speed up the entire process, allowing time and cost reduction. The analysis of the usersô experience with a product can give us hints about whether they like\dislike the product, whether the product features are appealing or not, etc. Therefore, authorsô belief is to perform that analysis developing a realistic simulation of the new product concept, in order to monitor the experience and the perception that users have of the product features, and eventually modify those features when not satisfactory. The expected benefit from this practice concerns the fact that the analysis can be performed also in the earlier stages of the product development, when changes are still possible and not costly.

Actually, due to the limits of available technologies and especially those for simulating the sense of touch, the implementation of effective interactive Virtual Prototypes is not straightforward but it requires:

- an integration of virtual information and real components in order to overcome limits connected to the use of a pure virtual prototype, i.e. **the shift from virtual to mixed prototyping is necessary**;
- a proper integration of the sensory modalities that intervene during interaction, and an accurate use of the information conveyed to the human perceptual system so as to obtain the desired effect during the interaction with the simulated product. The creation of a **multimodal interaction environment** is then necessary**.**

The paper describes the study and the development of a Mixed Prototype based on a multimodal interaction model including vision, touch and sound: it will enable us to perform analysis of aspects related to usersô experience with products. We discuss about what can be reproduced with the available technologies and how the strategy of integrating Mixed Prototypes with a multimodal interaction model can help in overcoming technology limits. A case study provided by a company working in the field of consumer products (www.indesitcompany.com) has been developed to test the proposed method. Company experts have shared their technical, marketing and managerial experience about the case study product, the home appliances market and the process they currently implement to validate interaction-based aspects. They also tested the application developed to validate the method providing authors with feedbacks about its potentials and limits, as well as suggestion for further improvement before involving real product testers. They have also guided the selection of the case study product: a specific fridge freezer model has been chosen exhibiting a distinctive three doors design with embedded handles.

2 RELATED WORKS

The involvement of final users in the product development process is particularly important since, even if a product might be the best from the technological point of view, however it may elicit a very poor emotional response in the users that will target the product as not appealing. Therefore, the study and understanding of the emotional response and appreciation of the product concur in designing better products in terms of marketing success [4, 5]. Physical prototypes work as the experimental set-up of emotional response evaluation tests, enabling the end users to physically see, touch and interact with the product. Alternatively, in industry a common, not expensive, but limited practice is to use only the visual representation of the product.

One of the recent trends in the Product Development Process (PDP) is the substitution of physical prototypes with their virtual replica; they are flexible to changes, especially during design review sessions, and less expensive [2, 3]. That substitution would make available several and not costly intermediate versions of the new product concept before coming close to the final solution.

Visualization technologies have now reached a high level quality in information reproducing, even with recent cost reduction [6, 7], thanks to the interest they attracted within the research community for decades. These technologies have been studied more than haptic ones [8] indeed in years most of the tests performed on Virtual Prototypes have been limited to visualization aspects as for example those described in [9]: in this work examples are reported of tasks concerning product evaluation tests performed when visualization is the unique available communication channel. These environments are appropriate for the evaluation of aesthetic aspects of products, as variants of colors, textures and materials in different lighting conditions, but not for the evaluation of other features, especially those related to users' interaction.. The possibility of physically touching and manipulating, and also operating and interacting with an object, is a critical requirement for consumer products assessment; the evaluation of the physical interaction by means of ònon-physicaló components is definitely poor and does not provide useful results.

Simple haptic control devices, such as knobs and buttons, have been developed for testing user interaction with the interface components of consumer products [10, 11]. The user is able to evaluate different pre-defined haptic behaviors of the knob and choose the favorite one. The fidelity of the representation of the haptic behavior of the knob is high, but the test of the user interaction with the product is limited to the knob, while other parts that concur to create the overall impression of the product are not considered. Another limitation of this procedure is the fact that the virtual environments are multimodal, mixing haptic and visualization technologies, even if not in stereoscopy, but do not include any sound. Actually, three key steps are considered fundamental in order to avoid the risk of tests results altering due to the information lack or incompleteness: 1) rendering visual information in stereoscopy; 2) including active exploration allowed by a tracking system; 3) adding the sound channel.

An interesting contribution can be found in the field of sound, in what is called Sonic Interaction Design [12], i.e. the use of tangible interfaces and interactive sound simulations in the activity of sketching and prototyping the sound effects produced during the object manipulation. This is an application of the concepts and principles of the Interaction Design [13] specifically in the field of sound.

Finally in [14] it is described a multimodal system based on haptic, sound and visualization technologies to test human interaction with Virtual Prototypes. Haptic feedback is returned through a 6DOF haptic device equipped with a generic handle. Force models are not accurate but similar to the real ones; for example the magnitude of the forces/torques returned through the device are based on rough kinematic models and on a subjective comparison and refinement between the real and the virtual model. A single sound for each colliding component is recorded and played, and it is not connected, for example, to the speed of the collisions between components. This pilot study has driven the research activity described in [15]: the analysis performed on the real product is detailed, highlighting the efforts spent to create a virtual replica that behaves like the real product.

In this paper the authors describe the principles at the basis of the development of a Mixed Prototype based on a multimodal interaction model. The requirement for that model to be sufficiently òrealisticó is amply argued, as a guarantee of its effectiveness for the study of usersõ experience.

3 MIXED-PROTOTYPING BASED ON A MULTIMODAL INTERACTION MODEL

The aim of the research described in the paper is to analyze the experience of a potential consumer interacting with a product at the point of sale. The final aim is to improve the comprehension of issues related to the emotional response and perceived value of products, and to transform these into design specifications. In the authorsõ study the analysis is performed using a mixed prototype based on a multimodal interaction model instead of a full working physical prototype, as typically used in the current industrial practice.

As previously said, the selected case study product is a fridge freezer. In case of refrigerators, domestic appliances manufacturers are interested in analyzing the user experience during the interaction with the frontal doors and the internal elements at the moment of purchase. The shift from the use of detailed, time-consuming and costly physical prototypes, to the implementation of mixed prototypes based on multimodal interaction, would then allow companies to anticipate these analyses and to quickly transform tests results into product specifications. Anticipating these analyses would reflect in a reduction of design errors and/or later changes, whose costs is high.

The main requirements to enable companies to correctly replace physical prototypes with virtual ones when performing this kind of tests are:

- users should be able to interact naturally with the simulated product, involving the same senses acting during the interaction with the real one. It means that the interaction environment should be multi sensorial and multimodal, involving in this case three senses: touch, hearing and vision;
- the quality of the information conveyed to the user should be the same of (or at least comparable with) the real one. In case the technology is not able to reproduce information with high quality, as it happens for the haptic technology, this should be substituted by real information. It means that in order to overcome technological limitations mixed prototypes at the moment represent the best solution.

In this Section, authors firstly describe the principles at the basis of the development of the multimodal environment that allows a **ò**natural**ó** interaction with the simulated product, and then underline how high quality level information can be reproduced by means of a mixed prototype.

3.1 Multimodal Interaction

For years virtual prototypes have been solely based on visual representations of the products for reasons related to the evolution of Virtual Reality (VR) technologies. Consequently, the kinds of tests returning useful results for the PDP have been highly influenced by this limitation. It is clear that in order to substitute a physical prototype with a virtual replica it is necessary that we can perform the same tests and obtain comparable results. If these tests are related to human interaction, where in the real experience more than one sensorial modality is involved, the interaction environment should include the same perception channels, by using dedicated technologies. In the VR field this is usually indicated with the terms *multimodal interaction*.

When creating a multimodal environment, for performing usersõ tests, the two following requirements should be addressed:

- **the interaction should be “natural” and enabling technologies should not interfere with the task in which the user is involved**, by altering the results. One of the mistakes that can be easily noticed when examining multimodal Virtual Reality environments is that in order to communicate through different modalities, the user is often asked to wear a number of devices that are so cumbersome that can alter the results of the tests performed;

- **each sense should be considered independent from the others, and a dedicated functional model should be implemented**. It means that for each sensorial modality involved in the interaction we should implement a simulation that is not necessarily connected to the ones implemented for the other senses. This choice allows designers to easily experiment situations where images, sounds and forces are not connected, enabling not only the analysis of each contribution but also the possibility to let them concentrate on the overall effect perceived by the user rather than on the causes that have produced it.

While the importance of the first requirement is evident, the validity of the second one can be demonstrated considering the field of sounds. Indeed, even if product sounds are strictly connected with its geometry and materials, one can also find examples [16,17] where those sounds are not the consequences of these choices: designing the most appropriate sound associated with a closing door, represents a well-known challenge for automotive manufacturers. In these studies is described how a sound is associated with a specific brand by end users, and how the preferred sounds chosen on the basis of a perceptual analysis can be mapped into design parameters. If we implement a prototype where visual aspects are separated from the haptic behavior and the sound emitted, we can run experiments on a multimodal experience where the sound can be the characteristic of the brand, the force can communicate robustness, and the visual appearance can communicate pleasantness. If the models are parametric we can tune these behaviors until an optimum is reached, and we can eventually extract the design specifications of the product. That validation strategy is not feasible in the current PDP practice by using early prototypes [18] since they are a poor representation, sometimes too simplified, of the final product. Indeed a common approach in industry is that the prototype built to reproduce sounds is different from the one that is used for testing the force feedback, or reviewing its aesthetic/visual aspects. Since the perception of the final product is not a simple sum of the single perceptions, it is clear that the use of a multimodal environment offers a tool to perform analyses in a new and much more accurate way. Obviously, at the end of the product development process, one or more physical artifacts will be necessary also to test and validate product quality and performances aspects.

3.2 Mixed Prototypes

In [15] we have experienced what can be reproduced using commercially available Virtual Reality devices, and we have concentrated in particular on what can be reproduced with general-purpose haptic devices. It is clear that the haptic feedback obtained while interacting with the interface components of a real product is a combination of tactile and kinesthetic cues and that reproducing only forces and torques is not sufficient to create a faithful virtual replica of a real product. Devices that permit a full hand contact with a generic surface and that at the same time return to the user forces and torques are not yet available. One of the best approaches to reproduce a faithful interaction with interface components would be to sensorize and actuate the interface components of a physical prototype, but this is quite expensive and one cannot consider it as a flexible solution.

In our research we have developed a simpler and cheaper alternative to an actuated physical prototype. We started from the consideration that in a door the part in contact with the userὂs hand is not the full door but only the handle. So we have reproduced exactly the shape that is in contact with the hand by means of a rapid prototype, and it has been mounted at the end of a force feedback haptic device. In this way we can reproduce faithfully forces through the haptic devices and the pressure distribution on the hand, through the rapid prototype. We can even reproduce the texture properties of the part if the physical artifact is made of the same material of the final product.

The mix of real and virtual information (mixed prototypes) is particularly important since it allows us to overcome the limits of the current technology, and in particular of those related to the sense of touch. If the physical part is limited to the sub-part of the product that is in contact with the user's hand, even the development cost is limited.

The diagram in Fig. 2 represents the combined use of a multimodal interaction model and of a mixed prototype. We create a virtual prototype, which is the sum of 3 building blocks: 1) geometry, colors and textures (used for creating the visual appearance); 2) the functional model for forces; 3) the functional model for sounds. Missing and incomplete information for the sense of touch is reproduced by means of a *physical artifact*, which has the same shape and can have the same texture of the final product. Information for each sensorial channel is extracted from the Virtual Prototype and mapped through the appropriate device until it arrives to the human perceptual system that performs the integration, creating the perception of the prototype. We called that phase the *multimodal perceptual integration* (Fig. 2). *Haptic feedback* is already an integration of simulated forces and real shape and texture. Besides, it is integrated with information coming from the other sensorial channels. It is straightforward that the *perceived product* is the integration of real and virtual information that arrives to the user through a multimodal interaction environment.

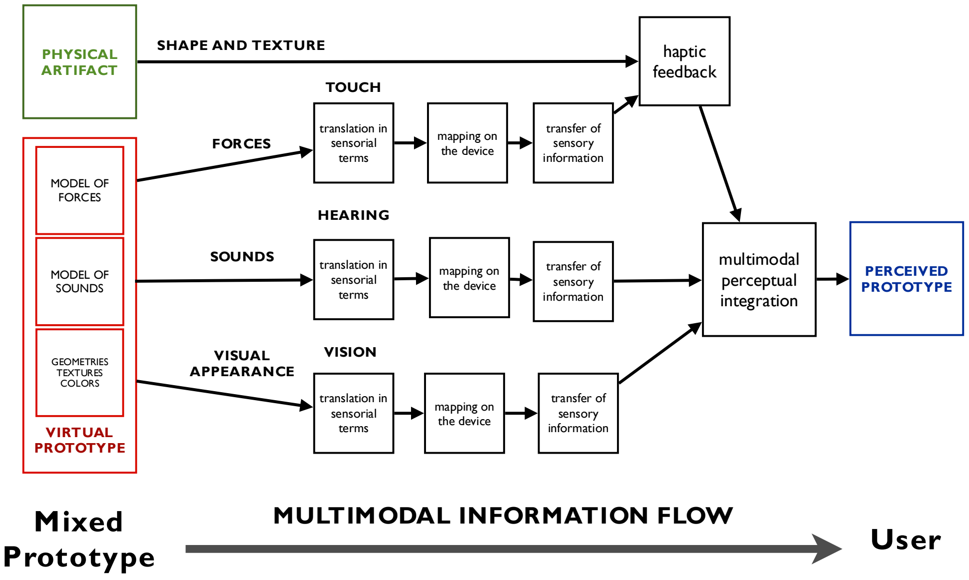

Fig. 2: The information flow going from the Mixed Prototype (Virtual Prototype + physical artifact) to the user through the three sensorial channels.

4 IMPLEMENTATION OF THE MIXED PROTOTYPE

In this Section we describe the main steps of the implementation of the case study provided by Indesit Company. The full process of data acquisition, starting from the real product, and translation into sound and force functional models for the Virtual Prototype is described in [16]. The need to acquire data from the real product does not constitute a limitation for the method. Indeed in industry, in most cases product innovation is based on changes to an already existing system or architecture: design improvements or new performances/features have to be implemented when new core-requirements for the product arise. Here, we firstly focus on the requirements for the creation of the multimodal interaction environment and then on the functional models for the three sensorial channels that compose the mixed prototype (see Fig. 2). In particular we concentrate on the model of forces and sounds, which are implemented using two different approaches. Finally we focus on the creation of the physical artifact that transforms the prototype from virtual to mixed.

4.1 Interaction Scenario and Main Requirements for the Application

Before developing the application, we have figured out a scenario of use of the mixed prototype through our multimodal environment. That scenario is structured as follow:

- Phase 1: the user is free to visually explore the prototype so as to evaluate visual appearance in a natural way, i.e. the images get adapted to his point of view;
- Phase 2: the user informs the application developer about which component of the fridge freezer he wants to interact with;
- Phase 3: the haptic device is moved to the appropriate position respecting the real product height and proportions (Fig 3 on the left);
- Phase 4: the user grasps the end effector of the haptic device that has been prototyped so as to have the same shape of the corresponding òhandleó of the real door/drawer;
- Phase 5: the user experiences the pre-defined effects assigned by the application developer, and after he can ask for changes until his desired force/sound effects have been reached (Fig 3 on the right);
- Phase 6: since the session is recorded in a log file, the mixed product final configuration can now be stored. Input data are then available in terms of product specifications;
- Phase 7: a team of designers could make use of that data for updating the existing product or creating a new one.

Fig. 3: Phases 2 and 5 of the scenario of use of the mixed prototype: the physical artifact is moved to the right position by the haptic device and the user is able to experience the pre-defined effect asking for some changes.

One of the fundamental requirements of our application is that the multimodal environment is transparent to the user, i.e. that the user does not feel to interact with a simulated world, mediated by external devices. This would decrease the sense of presence that in this kind of application is very important. The application should be intuitive to use, so that it does not require a long period for familiarization. That aspect is strategic for the tests validity since the population of potential users have to be searched not among VR technology experts or practitioners but, more broadly, among product potential users, following the guidelines of the company marketing department.

Therefore, a list of key requirements for the application can be summarized as follow:

- the test should be performed in a one to one scale condition: the dimensions of the visual and of the haptic models should be the same of the dimensions of the real product;
- the visualization environment should include the visual model of the product, with a rendering quality similar to the real one. No Graphical User Interface (GUI) items should be included into the environment for avoiding distractions. An expert is needed to run the application and it is not necessary that the user learns how to modify parameters by means of GUI elements;
- to guarantee a natural visual exploration of the object, the user's point of view must be tracked and the image continuously adapted. It is important that the visual model is superimposed on the haptic one, so the user is able to see and touch the component in the same point;

- the user should handle a shape that is the same of the corresponding real one, since kinesthetic and somatosensory cues might be different from the expected ones when using a different contact shape;
- regarding the auditory sensorial channel, the sounds should come from the point from which they are emitted in the real product and should be realistic.

4.2 Hardware and Software Setup

On the basis of the requirements, the choice of the hardware and software setup is the following (as illustrated in Fig. 4):

- *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;
- *a 3DOF MOOG-HapticMaster* (www.moog.com/products/haptics-robotics/) equipped with the prototyped handle;
- *a single speaker* for the sound rendering has been positioned under the haptic system. The position of the speaker has been chosen so as to be in the middle among the two drawers and the door;
- *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.

Finally regarding the software tool the application has been developed using the H3DAPI opensource library (www.h3dapi.org) that supports several haptic devices including the MOOG-Haptic Master. It is based on the open standards OpenGL and X3D for the visualization, and OpenAL for sound rendering.

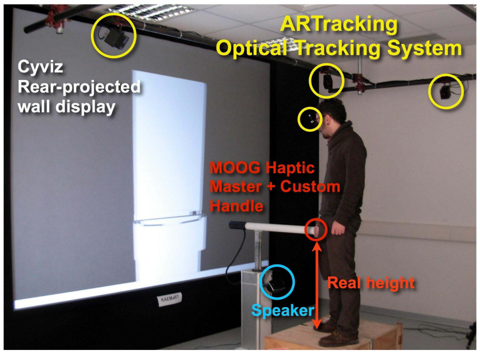

Fig. 4: Hardware setup consisting in a 3DOF haptic device equipped with a custom handle, a speaker, a rear-projected wall display and an optical tracking system.

4.3 Analysis of the Real Forces and Implementation of the Haptic Environment

The force model is not computed from geometries through physics-based algorithms but it runs separately in the simulation, i.e. it can be modified even preserving geometries. That model has been defined first theoretically on the basis of a geometry-based analysis, starting from CAD files, and then practically, adapting the model on the basis of data acquired from measurements performed on the real product.

We were interested in calculating the forces exerted on user's hand while opening/closing the doors, in order to create the same effect on a force-feedback haptic device. For example, regarding the fridge freezer central door, we observed that the force effects returned to the user's hand in the direction orthogonal to the door itself, is initially due to the suction effect of the seal, and of the two springs acting in parallel and having different spring constants. After this initial effect, the force is a combination of inertia and friction.

First we have simplified the model by assuming that the force can be represented as an interval function composed by first order functions, even for the seal suction effect. While the spring behavior can be calculated from a technical datasheet, the suction effect of the seal cannot be easily extracted from CAD models. To get that effect we have run measurements on the real product using a compression donut load cell (FUTEK model LTH300, www.futek.com) with a maximum detection load of 445 N. The load cell has been mounted between participantsõ hand and the door handle in order to measure the required opening force as a function of time. Then we have used the AR-Tracking optical tracking system (www.ar-tracking.de) to detect the position of a marker set glued on the door, which has been used to compute the door displacement as a function of time (Fig. 5). Using that data the authors adapted the simplified parameters previously defined so as to include even the effects that, in a CAD model one cannot distinguish and calculate.

The sensors have been triggered and the data have been acquired with the same rate (60 Hz). Then we have plotted force values as a function of time. Three participants have been engaged for a total of 12 acquisitions: they have been asked to open the door with different average speeds comprised between 0 and 300 *mm/s*.

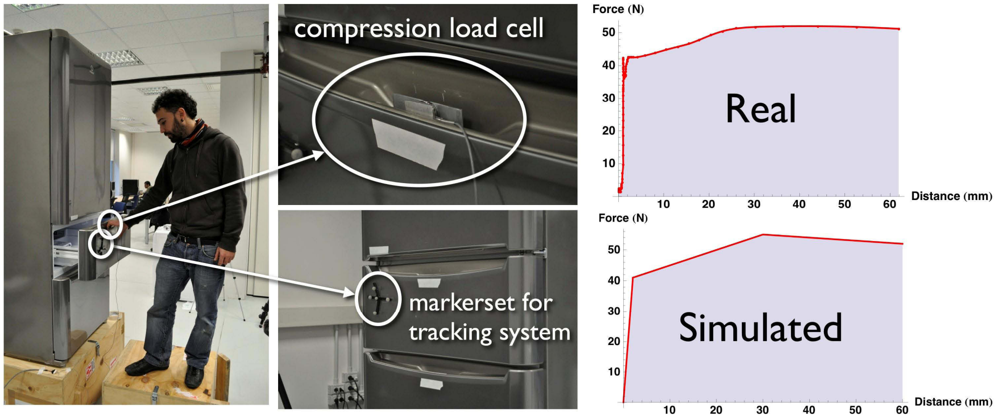

Fig. 5: The sequence to reproduce the force feedback effect on userõs hand: (1) forces values acquisition from the real product; (2) data elaboration; (3) haptic feedback simulation.

For the implementation we took into account a couple of major requirements. First, the force effect must be obtained as a combination of haptic primitives that reproduce the physical principles that in the real prototype generate that specific force. This means that a real spring should be reproduced with a haptic spring, and friction with the same law - if available -, otherwise a similar force effect should be implemented. In addition, the force model implemented can be also changed and tuned in order to meet user's preferences, enabling the model itself to be translated into clear technical specification. This requires that when the user asks for a change of the haptic behavior, the application developer is able to promptly recognize the corresponding primitive and the related range of values to modify: using a unique complex function to represent all displacement ranges has seemed not to be an effective strategy to follow when a direct mapping of force model into product specification is necessary. For example, for the fridge freezer central door, the force effect is obtained with two haptic springs, the first one acting in the first range of displacement of 2 *mm*, the second one in the second range that goes from 2 to 30 *mm* with a pre-load of 40 *N*, and in all the range a continuous viscous damping effect reproducing the sum of the friction and of the inertia. Fig. 5(3) shows the comparison of the real and simulated force effect for the drawer at a speed of 0.025 *m/s* (mean between the maximum and the minimum speed detected during the acquisition).

In order to constrain the haptic device to move as the handle of the real product, (a translation constrain for the second and the third door and a rotation around an axis for the first which is the fridge one) we have introduced some haptic geometries that are not visually rendered and that behaves as haptic magnetic rails. Then, in order to reproduce the translational and rotational limits of the three doors authors have introduced rigid walls that are not visually rendered: the impact between the sphere (the end effector of the haptic device) and a wall (the translational or rotational constraint) guarantees the limits respect.

Finally, to increase the quality of the interaction with the virtual components in terms of pressure distribution on the user's hand and joint/tendons, an element has been prototyped and screwed to the end effector of the haptic device. This element reproduces exactly the geometries of the three doors handles. As visualized in Fig. 6, the upper part of the prototype represents the handle of the second and third door (the central and the bottom one), while the bottom part of the prototype reproduces the first door handle. The shape of the element and the angle between the two handles take into account both the kinematics of the real object and the limits of the working volume of the MOOG-HapticMaster, maximizing the opening angle of the upper door, while minimizing the amount of material used.

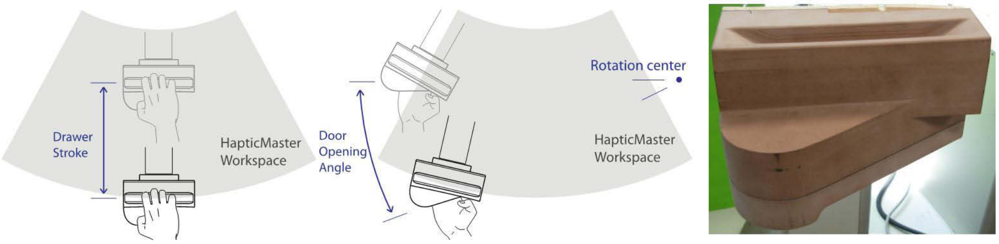

Fig. 6: The shape of the physical artifact has been defined in a way that maximizes the use of the working volume of the haptic device, and minimize the material used.

4.4 Sounds and Psychophysical Approach

The sound model is not based on synthetized sounds, computed through physics based algorithms, but on real ones recorded from existing products; they are played and adapted to the speeds of colliding components. We decided to adopt a psychophysical approach [19] to reduce the number of sample sounds that should populate the assigned database, i.e. to play different sounds only when they are perceived as different.

We have recorded a set of different sounds, during the act of door opening/closing, each time demanding to repeat the act varying the gesture velocity, to the subjects involved in the test. Then, we evaluated how much a velocity should vary in order to produce a sound that subjects recognize as related to a different velocity of the door displacement. That information has been used in the implementation phase to reproduce all the range of velocities by means of a limited series of sounds perceived as different.

This approach that is basically based on psychophysical principles has been implemented in the following way: a database of 20 sounds related to 20 different velocity intervals has been created. The hardware setup used for the recordings mainly consists of a microphone (Shure beta 58A) and a sound card (M-Audio firewire 410). The velocities have been captured using the ARTracking optical tracking system. A marker-set has been glued to the door.

As an example, regarding the central door, which is characterized by the translational constrain, authors identified three main sounds to describe the entire opening/closing stroke:

1. the impact of the door when it is completely opened (corresponding to the end stroke). The velocity for this sound was computed as the mean of the velocities corresponding to the last 50 mm of the door stroke in opening.
2. the internal impact of the two rails; it occurs at a certain point during the door closing.
3. the impact of the door in closing. The velocity interval for this sound was computed as the mean of the velocities corresponding to the last 50 mm of the door travel during the closing. The door does not produce any significant sound at the opening.

We have analyzed the 20 audio tracks, for extracting the position/velocity profiles and for correlating the velocities with the sounds. Then we have selected five samples for each sound (opening, closing and rail impact as shown in Tab. 1), by taking into account that the velocity interval between each sample and the next one should have to be as much similar as possible.

Three different tests have been performed involving five subjects (aged between 23 and 37, all males). Participants were seated in front of a computer screen, and were asked to wear headphones (AKG K240). When the experimenter started the test session, the participants listened the reference stimulus (Stimulus 3 in Tab. 1) followed by a test stimulus. The task they were asked to complete was to indicate which sound was related to a major velocity of the door, with a Forced Choice paradigm [19]. Each session was composed by five different couples of stimuli (reference stimulus + test stimulus) randomized and repeated 10 times (5 couples x 10 repetitions). Subject wrote their answer themselves. Each session lasted 25 minutes.

Authors fitted a cumulative Gaussian distribution to the percentage of judgment in which the test sound was considered produced by a lower velocity of the door for each subject and session. JND (Just Noticeable Difference) was defined as the 84% of correct responses and an estimate was provided for the variability of the underlying Gaussian distribution.

$$JND = \sqrt{2} \cdot \sigma \tag{8.1}$$

Stimulus	*Opening (mm/s)*	*Rail Impact (mm/s)*	*Closing (mm/s)*
1	162	309	210
2	231	352	282
3	247	378	310
4	284	400	353
5	304	416	403

Tab. 1: Stimuli used for the psychophysical experiment for setting the sound/velocity thresholds.

Analyzing the results of the psychophysics analysis we have decided to use a database of fifteen sounds previously recorded, whose related velocities differ at least as the $JNDs$ obtained. The mean and the standard deviation of the $JNDs$ that we obtained for each subject and condition are: 32.03 ± 3.54 mm/s for the opening, 38.04 ±6.1 mm/s for the internal impact of the rails and 21±2.07 mm/s for the closing.

During the implementation of the sound model, in order to play different sounds depending on the velocity of the haptic device, the velocity is captured when the haptic device is in pre-established positions (the one in which the sound should occur). This velocity is then compared with the database of sounds/velocities and the closer velocity value is found. Finally the corresponding sound is played.

5 CONCLUSIONS

The paper has described a methodology based on Mixed Prototype and a multimodal interaction model, which enables us to test human interaction with products since the beginning of the Product Development Process. This methodology allows companies to predict, test and improve the emotional response and the perceived quality of their products. The motivation of the research is related to the fact that designing the emotional response of industrial products is becoming more and more important since it is one of the key factors of the success of a product; in particular for products whose technological level is already sufficiently high to be the only key factor able to influence consumersô purchasing behavior.

Compared to current industrial practices this methodology presents a double advantage. Firstly it enables to anticipate the emotional response during the PDP because it allows creating a high fidelity simulation without the need of building costly and time-consuming physical prototypes, which are usually available only at the end of the development process. Then, it permits to rapidly test product variants: a physical prototype is not able to guarantee the same flexibility and rapidity. It is possible to test sound, touch and visual effects, which are mutually independent, in a multimodal integrated way, and to tune the combined effect until an optimum has been reached. The results can be translated into design specifications that can be used early in the PDP. Regarding that final step of translation authorsô belief is that advanced simulation approached can support the translation process; authors are now currently analyzing and validating their hypothesis, as a next step of the research activity described in this paper.

Authorsô methodology is based on the use of Mixed Prototypes that differently from physical ones are highly modifiable, so they reduce the need of building new prototypes when different product behaviors have to be tested. Mixed prototypes are more òrealisticó than virtual ones, because they permit to overcome technological limitations of the current devices in rendering information by means of the introduction of physical parts into the scene. The methodology is based on multimodal interaction where the senses are used in a ònaturaló way, trying to hide the Virtual Reality interfaces to the user. The paper describes in details the implementation of the mixed prototype and of the multimodal interaction environment, where a dedicated model has been created for each sense.

The concept has been proved on a real product provided by one of the European leading manufacturers and distributors of major domestic appliances.

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