Reverse engineering of interactive mechanical interfaces for product experience design

This paper proposes a method for guiding the redesign of product interfaces based on a reverse engineering approach

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Designing physical interfaces, like the doors of consumer products, able to elicit a positive experience when interacting with them, is now becoming a key priority for design teams. One of the main difficulties of this activity consists of translating all the qualitative perceptual feedback that can be captured from the customers into quantitative specifications. Performing this translation is not an easy task since there are still no effective tools, methodologies or approaches able to guide designers in accomplishing this goal. To overcome this lack a reverse engineering-based approach is proposed. This one guides designers towards the modelling, parameterisation and reproduction of the behaviour of the product interface to be redesigned, within a multisensory virtual environment. The intent is to let the user experience different behaviours in order to ask them to identify the desired one or to express preferences for updating it in real-time according to indications provided. At the same time a detailed physics model, built by the designer, is used to convert this desired behaviour, into detailed quantitative design specifications. The method is defined as a reverse engineering one for two main reasons: first the new interaction is derived on the basis of the behaviour of an existing interface, taken as reference, and second a reverse engineering of the user's perceptual preferences is applied to derive new specifications. A case study is discussed to demonstrate the method effectiveness and to highlight its limitations.

Keywords: interactive systems; virtual prototyping; product experience; haptics; reverse engineering

1. Introduction

In traditional engineering disciplines, systems are considered as black boxes able to transform a pre-defined input into a specific output. Interactive systems, meant as systems users can interact with, are more complex to handle. They accept variable inputs coming from different users (actions), and transform these into output (perceptions). Users are informed about the system status through their senses, and thus can intervene to perform changes.

Hence, an interactive system implies that one or more interfaces between the user and the system exist, enabling the first to come in contact with the second. According to Kortum (2008) these interfaces should no longer be limited to the 'traditional' Graphical User Interface (GUI) but should include all the elements that support the user in completing his/her task of providing inputs to and receiving feedback from the system, i.e. what the user does and how the system responds (Raskin 2000).

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These interfaces are characterised by a dynamic behaviour since an interaction typically occurs in time and space. This behaviour follows an action-reaction or action-perception law, depending if it is considered from the system or the user point of view (respectively, the first or the second). In both cases the action is the input given by the user. In addition, since multiple users can interact with them, the behaviour of an interface should be also ideally adaptable to different users.

As discussed in Kortum (2008), in designing these interfaces we should at least take into account the following aspects: their effectiveness in enabling the user to accomplish a given goal; their efficiency in reaching such accomplishment in terms of perform-ance; their capability in letting the user perceive a satisfying experience when interacting with the system. This last point is due to the fact that every time an interaction occurs an experience takes place (Forlizzi and Battarbee 2004), which is the result of a user subjective judgement of the product, in terms of 'good-bad' perception (Hassenzahl 2008). For example, it is demonstrated in literature that the interaction with the haptic interfaces of a product has a strong influence in marketing decisions, if it succeeds in eliciting a positive sensory feedback on the user (Peck and Wiggins 2006).

In a product design perspective, any kind of product must be considered as interactive (Bergman 2000). The door of a dishwasher can be seen as an interface of the product since the user has to interact with it in order to load the objects inside. Also its cabinet can be seen as an interface of the product, since it provides feedback to users in terms of e.g. the spatial occupancy of the product (i.e. its dimensions). Hence, the design of a product and, specifically of its interfaces, implies the consciousness of the aspects previously discussed and the consideration of the following requirements.

On the one hand, there is the need to map the entire dynamic behaviour of the product interfaces considering all the intermediate states they can undergo during the interaction, because each state influences the user's product perception. On the other, there is the need to assess the system (or product) reaction/perception in relation to a variable input: different users can interact with the same product and its reaction should be able to elicit a positive perception on them.

From the designer's point of view, it is fundamental that these two analyses are performed early in the design process i.e. when there are still the time and the economic conditions to perform changes on the new product. These studies require the active involvement of users (or company marketing experts) who should be asked to interact with different design variants of the interface. However, performing this kind of analyses by means of physical prototypes, as usually done in industry, is costly and time-consuming since the variants to test have to be accurately built especially if a high fidelity interaction is needed. Moreover, the designer does not have the possibility either to tune in real-time the behaviour of the product interface (according to the user's indications), or to test behaviours that are different from the ones already designed and validated with marketing experts before building the physical prototypes. Mainly 'Do you like? Yes-No' evaluations can be performed, without the possibility of exploring a broader range of solutions.

To overcome these issues in this paper we propose a methodology for modelling, simulating and experiencing an ideally infinite number of behaviours of a product interface. Specifically, the methodology is focused on the design of the haptic interfaces of products, since they enable a direct physical communication between the human and the system (Hayward *et al*. 2004), and strongly influence the user's sensory experience (Klatzky and Peck 2012). From the implementation point of view, the methodology is built upon the use of high-fidelity and parametric Virtual Prototypes (VP) and upon the simulation of the physics behind them. The methodology has been conceived as a reverse engineering-based approach since it starts from the analysis and virtualisation of an existing product, which acts as the baseline of the redesign activity. To test the methodology the redesign of the haptic behaviour of a dishwasher door has been used as a case study.

2. Human-in-the-loop in the design of interactive interfaces

For years interfaces and interactive systems have been largely studied in the Human-Computer Interaction (HCI) field where considerable effort has been spent in improving usability and ergonomics issues (Tullis and Albert 2010).

Indeed, in the HCI field, the more complex the interactive system to be designed, the earlier the testing and evaluation of the design properties have to be performed. That is why a considerable number of approaches are available in literature with this aim (Campos and Harrison 1997).

Actually, even the HCI field would benefit from an improvement in the conception and in the use of these prototypes. In fact, these should not be seen solely as a means for validating an alpha version code, but instead as working tools for exploring directly with users further technical solutions or tuning the ones already defined. The objective would be to capture in real-time the users' feedback and feeling about the system and put that information directly into practice (Hartmann 2009, Vermeeren *et al*. 2010). However, despite this growing need to improve the design of interactive systems (i.e. automatically recording users interacting with a system), the lack of appropriate and reliable tools makes this strategy difficult to apply (Kim *et al*. 2008).

In the engineering design field, the physics of the interaction process is described as an exchange of mechanical work (Colgate and Hogan 1988). Even the interaction with simple mechanisms such as doors and drawers demands both linear and non-linear forces, as well as the definition of a number of kinematic/dynamic parameters (e.g., trajectories, accelerations) for controlling the system behaviour (Jain *et al*. 2010). According to this perspective, when designing an interactive system what has to be conceived and thus modelled is the system the user interacts with. The simulation/model at the basis of the system behaviour should have the following characteristics: be stable, robust, parametric (i.e., flexible to changes) and be based on the parameters controlling the dynamic of the interaction (Sinha *et al*. 2001). Furthermore, when an experimental activity is required, prototypes of the interfaces of the system should be also available. These prototypes should be modifiable and parametric in order to test different kinds of interactions. They should be able to capture and/or measure the user action, and provide as output a real-time reaction. This is required because an experiment planned to recreate real product experiences should at least engender the same effects in a reliable way (Klein 2002). This is also the reason why these prototypes should be built upon the physics controlling the dynamics of the interaction. Fulfilling all these requirements making use of only physical prototypes, or 'digital' simulations of the interaction is not feasible.

A physical prototype is usually not largely modifiable and enables the user to experience one behaviour per time. Actually, their real limitation relies on the fact that when a physical model is built the detailed design activity has been already performed and thus the 'possible' behaviour of the interface has been already selected by the designer and not by the user. 'Parametric' physical prototypes may be built but they would be expensive, and in general less flexible than virtual prototypes. For example, it would not be feasible to decouple the haptic feedback of the product from the sound as virtual prototypes can do.

Another solution to this problem might be a fully digital simulation, where also the user is virtualised. To date digital simulations enable us to compute the forces and moments exerted by the handle on the user's hand, and consequently to estimate the forces on the user's wrist, elbow and shoulder. From a safety and comfort, and thus ergonomic perspective, this information is important. Software tools enabling ergonomic analysis already exist on the market. However, to date a full virtualisation of human behaviour does not exist in any software tool that allows us to simulate a full experience design testing (i.e. a virtual mannequin answering questions such as 'do you like this interface behaviour?', 'would you prefer to feel more or less force?', etc.). To date the only way to perform such an analysis is to put a real human in the simulation loop.

Focusing attention on the tools already available in literature for designing the behaviour of haptic interfaces, based on the inclusion of the human-in-the-loop, useful indications can be retrieved. Shin *et al*. (2012) and Strolz *et al*. (2011) describe the design of haptic interfaces able to recreate the sensation and thus the experience of opening respectively the door of a refrigerator and of a car. In Shin *et al*. (2012) the capability of this interface in rendering the behaviour of the real door is validated making use of the real product while the assessment of the similarity between the two behaviours (i.e. the virtual and the real one) is performed through tests with users. This 'human' assessment is fundamental for understanding if the haptic interface is ready to be used as a design tool for improving the behaviour of the real door. This approach clearly matches with the intent of this study, but further considerations have to be underlined before introducing the contribution of the present research.

For designing the (haptic) interfaces of products the haptic model of the device and the mathematical model controlling its dynamics are not sufficient to derive the technical specifications for designing the interfaces according to the users' feedback. Indeed, also the physics model of the interface should be correlated with the virtual one. This correlation should be performed in a way that the behaviour of the haptic device can still be varied in real-time in order to guarantee the flexibility and the reliability of the experience. The ideal situation for the designer would be giving the users the possibility to test an 'infinite' number of interfaces, or even better asking the users directly how they would change the behaviour of the interface, and immediately implementing it in the prototype. Both cases require the availability of a parametric prototype of the interfaces.

Finally, as has been demonstrated in Bordegoni *et al*. (2011) and Bordegoni and Ferrise (2013), the creation of a multi-sensory environment involving at least three senses such as vision, touch and hearing is an important requisite in order to properly recreate a complete product experience. The interaction should be as 'natural' as possible, and each sensorial modality should be modelled or simulated independently from the others in order to let the designer create a mix of experiences, and/or evaluate the impact and contribution of each sensorial channel on the overall product experience (Ferrise *et al*. 2013a). For example, a specific sound may be represent-ative of a product brand, or a force may influence the perception of the robustness of the product.

Hence, starting from all these considerations in this paper a reverse engineering-based methodology for designing the beha-viour of the haptic interfaces of products is proposed. This methodology is discussed in the following section and it is also the result of a three-year experimental work (Graziosi *et al*. 2013, Phillips Furtado *et al*. 2013, Ferrise *et al*. 2013a, 2013b, 2013c).

3. A reverse engineering methodology for modelling and designing the interaction

In designing a new product it is a common approach in industry to start from a reference product, usually already available on the market. This approach is reasonable for two main reasons: (1) with the new product being an improvement of an existing one, changes have to be applied directly on the architecture of the existing one in order to save time and money; (2) analysing what is good/bad in relation to the current situation makes the learning process more effective, enabling the identification of the causes of a problem. For these reasons, designers apply what in literature is defined as a reverse engineering approach: the design process of the reference product is reviewed before starting its redesign activity (Otto and Wood 1998). Actually, it is not necessary to review the whole product but just the components/ subsystems that are the focus of the redesign activity.

According to Otto and Wood (1998), a proper reviewing activity consists mainly of the following two steps: (1) identification both of the physical principles and of the relationships existing among the components of the product determining the product behaviour; (2) creation of the models describing those physical principles. These models are necessary in order to perform the simulations and tests needed to compare the current instantiation (i.e. the current technical solutions implemented) with the new possible alternatives (i.e. the output of the redesign activity). Once these steps have been performed, a redesign activity could start based on the outcomes of the reverse engineering and modelling-analysis stage.

In defining our methodology we have integrated the considerations previously discussed, since the reverse engineering approach is amply used and appreciated in industry, with the following research needs: (1) directly involving the users in the design process by collecting their feedback in real-time while they are interacting with the prototype of the interfaces (Kim *et al*. 2008); (2) automatically transforming these (qualitative) feedback, into clear design specifications. In order to fulfil these needs, interactive Virtual Prototypes (iVPs) (Bordegoni *et al*. 2011) have been used, since they enable the inclusion of the human-interaction component in the analysis (Wang 2002) and, with respect to physical prototypes, the possibility to quickly and easily render different variants. A schematic representation of the proposed methodology is shown in Figure 1.

3.1. Analysis and experimental characterisation

The first step of the methodology consists of first selecting the (physical) interface(s) of the reference product that we intend to redesign. Once selected this physical interface is fully charac-terised in order to understand its current instantiation, as suggested in the work of Otto and Wood (1998). To do that, it is first necessary to identify the sensory stimuli that the interface (and its behaviour) elicits (e.g. touch, vision, audition). This understand-ing is fundamental for two reasons: (1) to guarantee, later on in the methodology, the fidelity of its virtual representation (which will represent the starting point of the testing activity with users); (2) for planning dedicated tests to measure separately the contribution of each stimulus to the overall interaction.

Then, the components/subsystems of the product which have a role in generating/influencing the behaviour of the interface (e.g. the ones controlling its movement or position) must be identified. This analysis is useful for the next phases when a detailed study of the dynamics and kinematics behaviour of the interface is required: how does the subsystem(s) or component(s) previously identified interact, so that the interface performs that specific behaviour? What is their role in the interaction and in determining the sensory stimuli?

Finally, the analysis of the reference interface ends with an experimental characterisation of its behaviour (e.g. the acquisition of its time-dependent position or the force applied on it by a user during the interaction).

On finishing the first step the next two steps (‘Detailed modelling’ and ‘High-level modelling’, Figure 1) can be performed in parallel. Specifically, we propose a two-level modelling representation of the interface behaviour, one detailed and the other one performed at a higher-level. This approach is necessary on the one hand to have a full representation of the physics phenomena occurring during the interaction, and on the other to benefit from a model of the interaction that is computationally sustainable, i.e. rendered and modifiable in real-time. This requirement is fundamental in order to guarantee the fidelity of the virtual experience rendered.

3.2. Detailed modelling

In order to get the detailed model of the physics determining the behaviour of the interface, it is necessary to perform the following activities. The model is determined through an initial identification of the time-dependent physical phenomena occurring during the interaction. This requires taking into account all the physical domains (e.g., hydraulic, thermal, mechanical, …) involved in the interaction as well as the subsystems/components previously identified. Since the main objective of the methodology is to guide the redesign of the

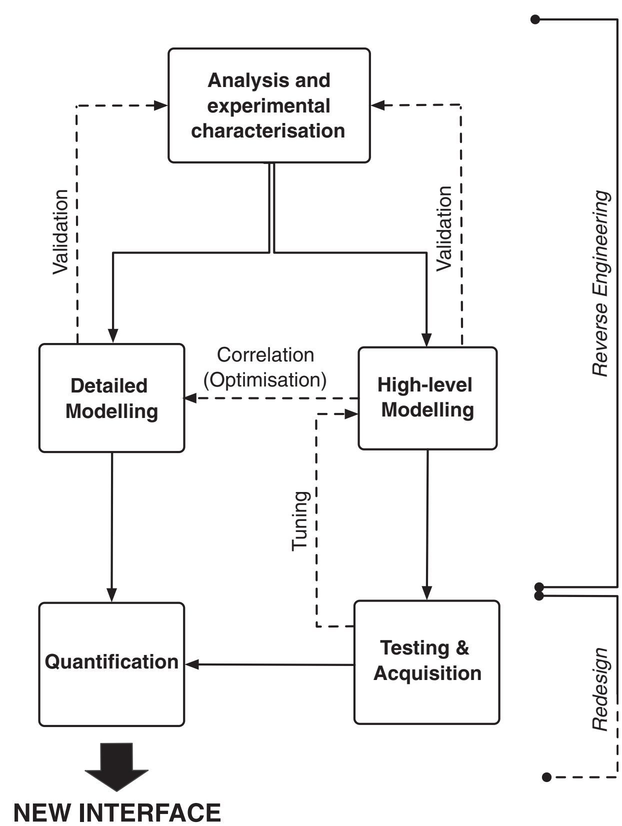

Figure 1. The main steps of the proposed reverse engineering-based methodology for designing the interaction of humans with the interfaces of a product.

product interface it is also necessary to identify a list of design parameters whose value can be modified. The choice of these parameters is up to the expertise of the designer, who decides design priorities or constraints according to the company. For verifying the correctness of the model defined, the experimental data acquired during the first step of the methodology i.e. 'Analysis and experimental characterisation' will be used as input for the model: when the values of the reference interface are assigned as values of these parameters, the output of the simulation should match with the acquired behaviour of the real interface. If it happens that the data acquired during this experimental characterisation are not sufficient to completely validate the model, a 'Validation' loop is necessary (Figure 1).

3.3. High-level modelling

The second model to build is the high-level one representing the human-interaction component that will be implemented through a multisensory set-up. This set-up will be prepared to perform the experimental tests with users. At this point of the methodology, it is clear what the sensory stimuli involved in the interaction are. This information is now here used first to select the tools and the physical interfaces that will be needed to render the interaction (e.g. a haptic device/handle for the kinaesthetic stimulus or one or more loudspeakers for the sound) and, second, to define the layout of the set-up (e.g., where the loudspeaker will have to be placed). It will be also necessary to investigate how these physical interfaces will have to be adapted in order not to alter the fidelity of the rendering (taking into account the intrinsic limit of any Virtual Reality technology).

Once the physical interfaces have been selected, the models to be used for controlling the human-interaction component (MacLean 2000) have to be defined. As for the selection of the design parameters done in the 'Detailed Modelling' phase, it is up to the designer to decide what sensory stimulus will be modified in real-time during the tests in order to let the user perceive different experiences. For each stimulus a parametric high-level mathematical model will have to be defined. For example, for rendering a variable related to a haptic stimulus it is necessary to properly control the haptic device; while for the sound it could be necessary to modify the sound rhythm, pitch and timbre (for details see Hermann *et al*. (2011)). More clearly, now it is necessary to identify the mathematical variables that can be tuned in order to generate different interactions. The mathematical functions have to be relevant with respect to the users' experience and do not have to simply reflect the design parameters of the physics behaviour. Hence, these functions should, as much as possible, correspond to the 'easiness' or 'smoothness' of a movement or to the pleasantness of a sound. The final outcome of this step is the human-interaction component that will constitute the interactive Virtual Prototype (iVP).

A further step is also necessary in order to guarantee the correctness of the models defined, and to correlate them with the physics model already built (see the 'Correlation' arrow in Figure 1). With the virtual models being defined as parametric, a specific set of values should give as output the behaviour of the baseline interaction, i.e. the one of the reference interface. According to this, these models can be validated not only empirically, by comparing the behaviour of the iVP with the one of the real interface, but also through optimisation algorithms: if the high-level models are correct the behaviour they describe should be correlated to the physics one. To perform this validation it is necessary to experimentally characterise the behaviour of the iVP describing the baseline interaction and use these data as input of the detailed model for retrieving the values of the design parameters describing the instantiation of the real interface. These values should be the ones of the reference interface.

3.4. Testing and acquisition

This phase of the methodology consists of asking users to assess different interaction experiences with the virtual interface of the product in order to identify the desired one. The scenario where the tests are performed is represented by the multisensory set-up previously defined. The users are invited to take part in this scenario and to interact with the iVP. The most effective way to perform this kind of test is to enable the user to ask for different experiences using his/her own words (e.g. 'I would like to have a softer closing', 'I don't like this sound, it's too harsh'). Leaving to the users the possibility to apply a control of the interaction is a key requirement in order to enable an effective user's engagement (Klein 2002).

According to the user's requests the designer will change, in real-time, the values of the variables controlling the mathematical models in order to consequently update the interaction. This is the reason why when building these models it is necessary to have clearly in mind what correlations exist between the functions defined and the sensations they represent (e.g. a softer closing would imply a gradual change of the variable representing the friction effect). Hence, the testing activity represents a fine tuning of the behaviour of the virtual interface with the intent of finding the desired one. Again, it is the role of the designer to make this process as 'linear' as possible by supporting the user in the modification process.

Once this desired interaction is available the final step of this activity consists of acquiring the new dynamic behaviour of the interface (e.g. its position as a function of time or its velocity).

3.5. Quantification

The characterisation of the desired behaviour of the interface is fundamental since, as previously done for optimising the models of the iVP, now the data acquired will be imported into the physics model to extract the values of the design parameters that should be used to physically recreate the desired interaction and thus, to design the new interface.

In the next section it is described how the methodology works in practice. The redesign of the door of a dishwasher is used as a case study. The product and the research activity context have been provided by Indesit Company (www.indesitcompany.com). Moreover, as already anticipated in Section 1, the focus of the modelling/prototyping and testing activities described in this work is the kinaesthetic stimulus generated by the behaviour of the door.

4. Experimental validation: redesigning the behaviour of the door of a dishwasher

4.1. Analysis and characterisation of the baseline interface

The door of a dishwasher is the interface enabling the user to access the internal cavity of the product. Opening and closing a door is a common gesture that one performs, usually, several times a day. Moreover this opening and closing activity is the first action a potential customer performs at the point of sale. As for the other white good products, dishwasher manufactures know very well how much this first impact/interaction with the product is important at the point of sale for influencing the buying decision. Hence, improving the pleasantness of the opening/closing of a door or of a drawer is an important part of the overall product experience and it is now becoming a strategic design requirement to satisfy.

The standard gesture for the opening consists in applying a force through the door handle for unlocking the door, and then continuing to apply a force for pulling down the door to a desired level. The closing gesture works in the opposite way, even if the amount of force required for pushing up and locking the door may be different. Hence the stimuli influencing this gesture are the following: haptic; auditory (i.e. in terms of the sound emitted and the vibrations generated) and visual (i.e. the door angular orientation and the handle position during the movement).

As illustrated in Figure 2 there are two main mechanisms generating the haptic feedback of the door. The first is a hinge mechanism placed at the bottom part of the dishwasher and through which the door is fixed to the front side of the cabinet. The hinge provides a proper balancing force to control the movement of the door, which can be seen as a planar circular trajectory, restricted to 90°. The second is a latch mechanism which is used to lock the door and consists of a plastic piece whose shape enables clipping the door into the locking system of the product. The schematic representation shown in Figure 2 represents the kinematics of each mechanism.

A planar articulated mechanism is responsible for controlling the force required to rotate the door. The plate has the purpose of transmitting a force, generated by the compression of the spring and the reaction of the frictions, in a desired manner, to the door. It has three extremities that affect the model, denoted as ‘A’, ‘B’ and ‘C’, forming a rigid solid body. The extremity ‘A’ is connected to the door through a rotating joint. The extremity ‘B’ is connected to the cabinet by a slotted link, where friction is also present, affecting the vertical displacement of the joint (it allows vertical translation and rotation). The extremity ‘C’ is connected to the spring and another friction. There is a static friction at point ‘D’ since the plate slides while moving on a rubber element. The hinge provides a proper balancing force, generated by the cumulative effects of the spring and of the frictions that interact with the articulated mechanism, in order to guarantee the stability of the door during its movement from the vertical to the horizontal position. The extremity ‘H’ of the plate is shaped in order to stop the door rotation when the 90° limit is reached by means of an end stop denoted as ‘S’. The latching mechanism (L) is simply represented as a spring-loaded one, since it can be seen as a stiff spring that generates, both in opening and closing, a reaction (compression) force against the one applied by the user. Only when a force threshold is reached does the door open/close. Only the tangential direction of the force applied by the user has an effect on the movement of the system.

To characterise the behaviour of the real door, the measurement of the force applied by the user has been performed by using a compression load cell (FUTEK model LTH300, www.futek.com) with a maximum detection load of 445 N. The load cell has been mounted between the user’s hand and the door handle (see also Ferrise *et al*. (2013b)) in order to measure the applied force as a function of time. The estimation of the state of the system was performed by measuring the velocity as a function of time with a gyroscope (British Aerospace Systems and Equipment unipolar gyroscope) capable of detecting angular velocities in the range of ± 100°/s, (simultaneously measured with the force applied by the user). The signals have been acquired at the rate of 5 kHz through the National Instruments NI cDAQ-9172 and NI 9125 analogue input modules (www.ni.com) and processed by means of the LabVIEW SignalExpress tool.

When the door is fully open, an impulse is given and the angular speed is measured by the gyroscope. There is no noticeable difference between the effort to move the door in one direction or in the opposite one, so it has been deemed sufficient to measure it in one direction only. It is also worth noting that since the force is applied by a human operator, the input of the system will always be significantly different for every trial and as a consequence, the output of the system will be also different. While the pair input/output changes at each trial, both in magnitude and shape, we are still measuring the

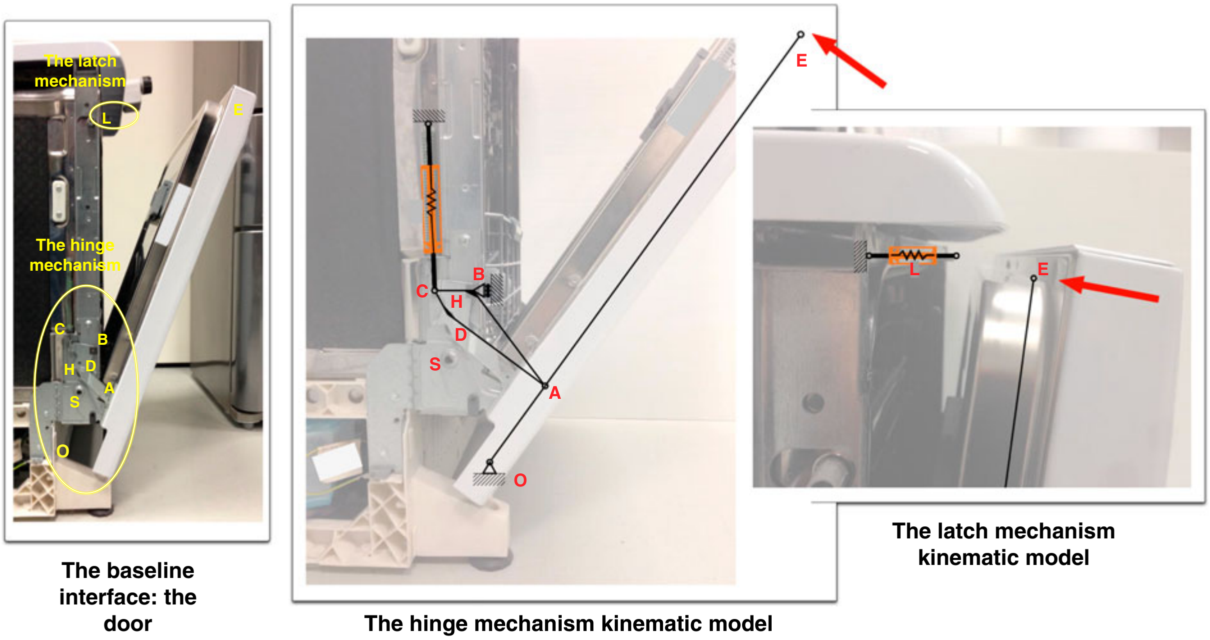

Figure 2. The analysis of the behaviour of the real interface: model of its kinematic mechanism.

response of the same system, and so it is expected that the estimation of the parameters will not change significantly. This means that when the optimisation process is performed for different pairs of input/output, the value of the estimated parameters for each optimisation should be very similar. In this way when the system is subjected to a new input, the difference between the outputs, once each set of parameters for each optimisation is set in the system, is not significant.

4.2. The detailed modelling of the physics behaviour of the door

The detailed dynamic behaviour of the door is modelled through the use of the commercial software tool LMS-AMESim (www.lmsintl.com). The level of the model, where each block represents an analytical equation, is reported in Figure 3. Some of the blocks directly correspond to the components of the physical system (e.g. the 'spring' or the 'plate') while others (e.g. the 'friction' and the 'relative speed') model the specific phenomena/events occurring within the mechanism. The relations existing among them are enforced through the connections applied on each block (i.e. the lines represent the input/output relations existing among the block and the flow of information).

The estimation of the relevant parameters of the dynamic model is done through direct measurement of the distances between each point, and the remaining ones indirectly, by measuring the dynamic response of the system due to an external force being applied. In the latter case, the force is arbitrary, and the estimation is done through an optimisation procedure that aims to find the parameters that allow the differential equations to behave as closely as possible to the results obtained through the measurements. If the solution of the optimisation problem is not unique, there will be more than a single set of parameters that satisfy it, which means that the values obtained might not be the actual values of the real

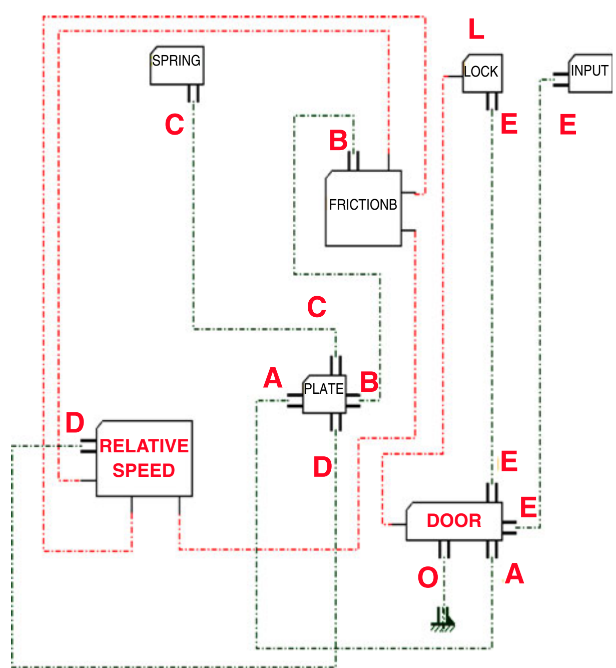

Figure 3. The detailed modelling of the behaviour of the real interface: model of the physics behind it.

system. Anyway this is not an issue, since the aim is to find at least one set of parameters that make the model behave like the real dishwasher door with a pair of input/output. The dynamic behaviour of the door of the dishwasher is described by the following equations:

$$\begin{aligned} \dot{x}(t) &= f(x(t),p) + g(x(t),p)\ F_u(t) \\ x(0) &= x_0 \end{aligned} \tag{1}$$

$$x(t) = \begin{pmatrix} x_1(t) \\ x_2(t) \end{pmatrix} \tag{2}$$

$$f(x(t),p) = \begin{pmatrix} f_1(x(t),p) \\ x_1(t) \end{pmatrix} \tag{3}$$

$$g(x(t),p) = \begin{pmatrix} g_1(x(t),p) \\ 0 \end{pmatrix} \tag{4}$$

where x is the state of the system, x_0 is the initial condition, $p = \{p_1, p_2,\ldots, p_i\}$ is the vector that contains the parameters to be estimated, and $F_u(t)$ is the input given by the user. The solution of the system can be represented as follows, even if it does not have a closed form solution:

$$x(t) = h(p, F_u(t), x_0, t) \tag{5}$$

If we can measure $x(t)$ and $F_u(t)$, knowing the initial condition x_0, we should find a set p that satisfies Equation 1, through an optimisation procedure, since $x(t)$, $F_u(t)$ and the elementary functions of f and g are known. Therefore, to estimate p, it is necessary to know the pair of input/output, which are the force $F_u(t)$ and the state, respectively. As already mentioned, there might be more than one set p that satisfies the imposed condition. The functions f and g correspond to the model in AMESim, represented by the blocks and the connections between them, while the set p contains the parameters relevant to the blocks, e.g. p_3 can be the value of the spring stiffness.

The state $x(t)$ is composed of the angular speed $\dot{\theta}$ and the angular position θ of the door, in relation to the ground. The entire state $x(t)$ does not need to be fully measured, since:

$$\theta(t) = \int \dot{\theta}(t)dt \tag{6}$$

As anticipated, the problem of finding the parameters of Equation 1 (present in the LMS-AMESim model) is addressed by describing it as an optimisation problem. In this case, as similarly done in Graichen *et al*. (2007), the objective function computes the maximum difference squared between the angular speed of the differential equations representing the model of the real system $\dot{\theta}_s$ and the measured angular speed of the door $\dot{\theta}_h$ for a given input force and at a defined interval:

$$F(\dot{\theta}_s(t)) = \max_{0\le t\le T}\ (\dot{\theta}_s(t) - \dot{\theta}_h(t))^2 \tag{7}$$

The optimisation problem to be solved is the following:

$$\begin{aligned} &\underset{\dot{\theta}_s}{\text{minimize}} && F(\dot{\theta}_s(t)) \\ &\text{subject to} && \dot{x}(t) - f(x(t), p) + g(x(t), p)F_u(t) = 0 \\ &&& x(0) = x_0 \\ &&& p_{min} \le p \le p_{max} \end{aligned} \tag{8}$$

where

$$\begin{aligned} x(t) &= \left(\theta_s(t)\ \dot{\theta}_s(t)\right) \\ \dot{x}(t) &= \left(\dot{\theta}_s(t),\ \ddot{\theta}_s(t)\right) \end{aligned} \tag{9}$$

The optimisation problem of Equation 8 can be solved with a genetic algorithm, already bundled within the LMS-AMESim software. For each pair of input/output, a set of parameters is found and consists of the following: the stiffness of the spring 'K', its pre-load force, the mass of the door, the moment of inertia of the door and its barycentre, the torque at point 'O', the torque at point 'A', the torque at point 'B', and the friction coefficients at point 'B', 'C' and 'D' (see Figure 2). Comparing the responses obtained, as exemplified in Figure 4, for a single experiment, for the angular speed of the door as a function of time, it can be noticed that an adequate approximation has been reached. We note that given the mass, the moment of inertia and the barycentre position of a rigid body, there is always another set of mass, moment of inertia and barycentre position that produces the same effect (both have the same moment of inertia in relation to the centre of rotation of the door, as a consequence of the Huygens-Steiner's theorem). In order to remove an additional parameter when solving the optimisation problem, it was assumed that the barycentre is located at the geometrical centre of the door.

4.3. The high-level model of the kinaesthetic human-interaction component

The high-level model has the role of representing the human-interaction component. According to the kind of interaction to be rendered, appropriate tools have to be selected. As already discussed, when interacting with the door of a dishwasher, haptic, auditory and visual stimuli are present. To render these stimuli in a multisensory set-up, the following devices can be used respectively: a haptic device; speakers for the auditory rendering; a rear-projected wall display for stereoscopic and scale visualisation (also Head Mounted Displays (HMD) can be used for this purpose, but the authors strongly believe that the use of HMD is not well suited for applications involving common users). In addition, it is also necessary to evaluate

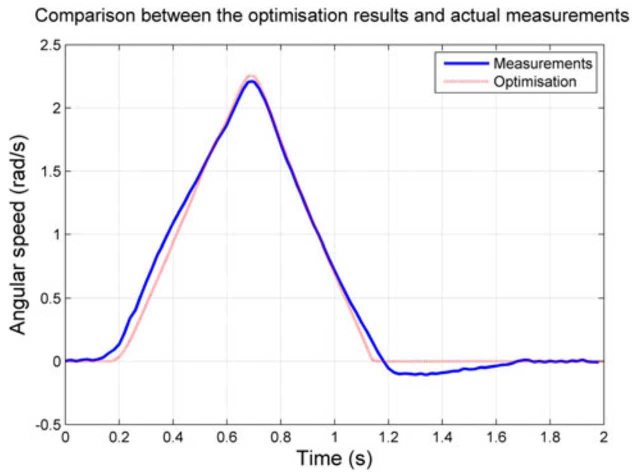

Figure 4. The door angular speed: comparing the measured behaviour (blue line) with the behaviour obtained through the optimisation process (red line).

how each device has to be adapted in order to guarantee the fidelity of the rendered interaction. For example, for the sound rendering it is necessary to find the proper location of the speakers (and this might not be sufficient, see Hermann *et al*. (2011) for further details); for the visual stimulus it is important to make use of an optical tracking system to capture the user's point of view position and orientation in real-time; regarding the haptic stimulus, due to the complexity of rendering the tactile sensation, the haptic device end effector (a MOOG-HapticMaster www.moog.com/products/haptics-robotics/) has been replaced with the real handle of the dishwasher in order to recreate the exact force distribution provided by the user's hand (see also Ferrise *et al*. (2013a)). However, as regards this last stimulus further and more detailed considerations have to be reported since the kinaesthetic sensation had to be not only rendered but also parameterised. These considerations are hereafter reported.

A great deal of haptic interfaces are nowadays commercially available. They can be classified as impedance controlled and admittance controlled devices. A more detailed discussion about each paradigm can be found in Hayward *et al*. (2004), Grunwald (2008) and Kern (2009).

The device used in this work, the MOOG-HapticMaster, is based on the admittance control paradigm. The choice of using an admittance control haptic device is due to the fact that the simulation of the dishwasher door requires both high stiffness and high forces. The HapticMaster measures the force exerted by the user, and an internal model calculates the position, the velocity and the acceleration a virtual object, touched in space, would achieve as a result of this force (Van der Linde *et al*. 2002). This vector is commanded to the robot, which performs the movement by means of a conventional control law, rendered at 2500 Hz. The device can apply forces up to 200 N.

The behaviour of the device is defined by a haptic model, which is a mathematical model responsible for computing the forces that the end-effector is subjected to, and defines the stimuli applied to the user hand when he/she is in contact with the same. According to the objectives of this research work, that model should represent the stimuli caused by the real system when the user is interacting with it, and not the actual dynamic system equations. However it is evident that both these two dynamic representations need to be roughly equivalent in terms of response to an input. This is the core consideration that allows performing the necessary simplifications that ease the real-time rendering. This approach allows a more intuitive understanding of how the tuning of a single parameter may affect the global behaviour of the system. This is because the strategy followed for defining the haptic model is derived by observing the perceived sensations. The equations to use have the following form:

$$\begin{gathered} X = [x, y, z] \\ F_h = (F_h, F_{hy}, F_{hz}) = F(X, \dot{X}) \end{gathered} \tag{10}$$

where F_h is the vector representing the forces that are applied to the end-effector, X the spatial coordinates of the end-effector and $\dot{X}$ their derivatives.

In order to make the haptic model correspond to the act of opening the door, it is necessary to constrain the end-effector to move along a curve that corresponds to the actual positions the real door can occupy in space, and evaluate what the main effects influencing the kinaesthetic sensation are, representing them in the equations. As the effects will be tuned in real time, it is important to describe them in an 'intuitive' way: functions should represent the stimuli, not the dynamic parameters of the real mechanisms (i.e. the hinge and the latch mechanism discussed in Section 4.1). Instead of using functions where the parameters correspond to a distance between two pivots or the specific friction occurring on one of the sliding components, the effects perceived by the user should be modelled: the parameters should correspond to the 'easiness' or 'smoothness' of un-locking/locking and opening/closing the door. In this way, the designer can more easily understand how modifying a value affects the user's perception of a new door behaviour.

In order to constrain the movement of the end effector along a curve, an attractive force, proportional to the distance between the actual position of the end-effector and the closest point belonging to that curve, is applied, together with a damping force. Since the dishwasher rotates around a fixed point, the trajectory allowed is along a quarter of a circle, so a virtual circle in space is created to be used as a reference at the haptic interface.

The main effect noticed when interacting with the door was the dry friction, which can be treated as a global friction and corresponds to the degree of 'smoothness'. The equations can allow different values of dry friction depending on the position of the door, and can also be applied asymmetrically. In the haptic model, we can also include viscous damping and the force that automatically enables the door to reach an equilibrium position.

The term responsible for the viscous friction is:

$$F_v = -c_v\ \dot{\theta} \tag{11}$$

A return force can be caused by a spring force, where the equilibrium point is at an angle θ_k, and its equivalent stiffness can change as a function of the position, if desired, and can be broken into different components arbitrarily, while the letter i identifies which component is being referred to. The magnitude would be:

$$F_{ret_i} = -k_{ret_i}(\theta)\ (\theta - \theta_k) \tag{12}$$

These forces can be activated or not using a combination of sigmoid functions that nullify their value once a threshold is crossed. Such a function can be described as:

$$S(\theta,\ \theta_i) = (\tan h(a(\theta - \theta_i)) + 1)/2\,,\ a > 0 \tag{13}$$

where a controls the slope. Each interval $[i - 1,\ i]$ defines the value of the force, and the overall force can be obtained by summing each component:

$$F_{ret}(\theta) = \sum_{i=1}^{n} F_{ret_i}(S(\theta, \theta_{(i-1)}) - S(\theta, \theta_i)) \tag{14}$$

The dry friction is modelled as a hyperbolic tangent:

$$F_{at} = -c_{at}\ \tan h(a\dot{\theta}) \tag{15}$$

The coefficient a defines the slope of the curve and c_at corresponds to the friction force magnitude. We can impose two different friction force magnitudes: one value when the door is closing ($\dot{\theta} > 0$) and another when the door is opening ($\dot{\theta} < 0$).

For $\dot{\theta} > 0$:

$$F^{+}_{dry_k} = -c^{+}_{at_k}\ \tan h(a\ \dot{\theta}) \tag{16}$$

For $\dot{\theta} < 0$:

$$F^{-}_{dry_k} = -c^{-}_{at_k}\ \tan h(a\ \dot{\theta}) \tag{17}$$

The dry friction force would become:

$$F_{dry_k} = F^{+}_{dry_k} + (-F^{+}_{dry_k} + F^{-}_{dry_k})\ S(\dot{\theta}, 0) \tag{18}$$

The same procedure can be applied for the viscous damping.

Friction can also change according to the angular position. In that case, sigmoid functions are also used to make the transition. For n transitions, we have:

$$F_{dry}(\theta) = \sum_{k=1}^{n} F_{dry_k}(S(\theta, \theta_{(k-1)}) - S(\theta, \theta_k)) \tag{19}$$

where friction remains approximately constant in the interval $[\theta_{(k-1)}\ \theta_k]$.

The final dissipative force F_{dis} would be the sum of the one caused by dry friction and the one caused by the viscous damping:

$$F_{dis}(\theta) = F_{dry}(\theta) + F_v \tag{20}$$

The vector of the force F_{dis} acts tangentially to the trajectory, and can be transformed into Cartesian coordinates by the application of a rotation matrix.

The final equation that calculates the forces generated by the haptic model, on Cartesian coordinates, is the sum of the dissipation and the return forces:

$$\begin{pmatrix} F_{hb_z}(\theta) \\ F_{hb_y}(\theta) \end{pmatrix} = \begin{pmatrix} F_{dis_z}(\theta) \\ F_{dis_y}(\theta) \end{pmatrix} + \begin{pmatrix} F_{ret_z}(\theta) \\ F_{ret_y}(\theta) \end{pmatrix} \tag{21}$$

The force feedback is the sum of the forces of the haptic model with the trajectory constraint forces (and eventually the forces that remove dissipation from the constraint forces, if deemed necessary):

$$\begin{pmatrix} F_{h_x}(\theta) \\ F_{h_y}(\theta) \\ F_{h_z}(\theta) \end{pmatrix} = \begin{pmatrix} 0 \\ F_{hb_y}(\theta) \\ F_{hb_z}(\theta) \end{pmatrix} + \begin{pmatrix} F_{x_k}(\theta) \\ F_{y_k}(\theta) \\ F_{z_k}(\theta) \end{pmatrix} + \begin{pmatrix} 0 \\ F_{y_e}(\theta) \\ F_{z_e}(\theta) \end{pmatrix} \tag{22}$$

The haptic model would correspond to the sum of the dissipative forces and the return forces, along with the radius to which the trajectory is constrained and its mass. It is equivalent to the following dynamic system:

$$\begin{aligned} I\ \ddot{\theta}(t) &= F_{dis}(\theta, \dot{\theta})R + F_{ret_z}\ \sin(\theta)R + F_u(t)R \\ &= f_h m(\theta, \dot{\theta})R + F_u(t)R \end{aligned} \tag{23}$$

where I is the inertia of system (kg m^2), whose value depends on its equivalent mass and the chosen value of radius.

4.3.1. Haptic interface transparency

In order to verify if the haptic interface could behave like the idealised haptic model we have performed some experiments. The user starts moving the virtual door, that at the beginning is at the fully opened state (90°), in equilibrium. The measured input is the force applied to the haptic interface in its z and y directions, and the measured output is the velocity of the end effector still in z and y directions. These measured quantities are converted into polar coordinates, in order to have the values in the tangential direction. As the door is constrained to move along a circle, the movement along the radial direction is negligible. In Figure 5 is illustrated a sample of the time history of the force applied by the user (sampling rate 2500 Hz), at the tangential direction, for one experiment. The value of the parameters for this particular experiment are reported in Table 1. This signal is then used as an input for the dynamic system of the haptic model (Equation (23)), which is numerically simulated. The output of the dynamic model used for comparison is the angular speed, while the measured values from the experiment are converted in order to represent them also as an angular speed. The comparison between the response of the simulation and of the haptic interface during the experiment can be seen in Figure 6.

According to this reasoning the model forcing the haptic device working as the door of a dishwasher and the mathematical variables for rendering different behaviours is now available and reliable.

4.4. Correlating the high-level model with the physics one

A consequence of the proposed methodology is that the dynamic system of the haptic model is not represented by the same differential equations of the dynamic system of the door, controlled by its mechanism. Therefore it might not be possible for the existing mechanism to reproduce the desired behaviour defined by the haptic model adequately, which would require either changing the way the original mechanism works, or another behaviour for the haptic model would have to be chosen (that is, either changing the value of the parameters of the haptic model, or changing some of the functions that represent its effects). Assuming that both dynamic systems can behave similarly, in order to find what the parameters are that allow the dynamic system that represents the real dishwasher door to behave in the same fashion as the dynamic system of the haptic model, the problem is formulated as an optimisation problem, similarly to how it was done in Section 4.2 (Equation

Table 1. Parameters used during the experiment.

Parameter	Value
$c^{+}_{at_k}\,(N)$	1.0
$c^{-}_{at_k}\,(N)$	1.0
$I\,(kgm^2)$	0.36
$c_v\,(N)$	0
$k_{ret_i}\,(N)$	0

(8)). The objective function of the optimisation problem revolves around the same idea:

$$\begin{aligned} F(\dot{\theta}_s(t)) &= \max_{0\leq t\leq T}\,(\dot{\theta}_s(t)-\dot{\theta}_h(t))^2 \\ &= \max_{0\leq t\leq T}\,\Big(\int [f_1(x(t))+F_u(t)g_1(x(t))]dt \\ &\quad -\int [\frac{f_{hm}(\dot{\theta}_h(t),\theta_h(t))+F_u(t)}{I}]dt\Big)^2 \end{aligned} \tag{24}$$

The only difference from the previous section is that instead of measuring $\dot{\theta}_h(t)$, here it is estimated through the use of the haptic model. Unfortunately, it cannot be known beforehand whether the dynamic system of the door can act in the same way as the haptic model with the chosen parameters. In practice, one would have to test and see if the results obtained from solving the optimisation problem yields good results. It is important to mention that whether the optimisation will be successful or not depends heavily on the amount of parameters and the selected boundaries. Inadequate boundaries could either not contain the optimal solution, or be so large that the algorithm fails to converge to a solution with acceptable error. The choice for these boundaries is not straightforward: for this problem, an initial guess was required, and multiple tests were run, where the interval of the boundaries was successively reduced, until the solution no longer changed.

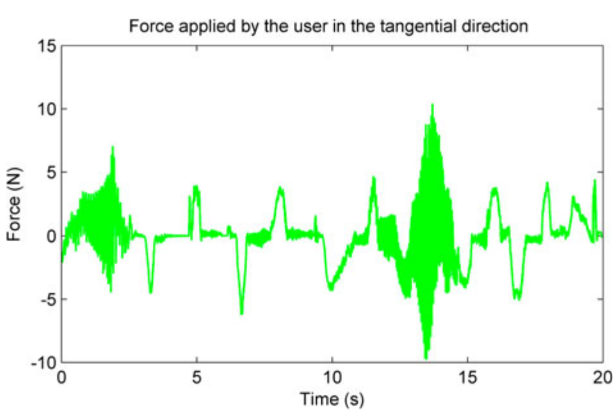

Figure 5. Force applied by the user during one experiment with the haptic interface.

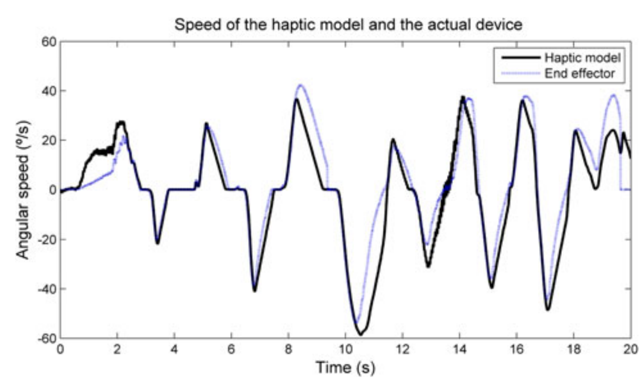

Figure 6. A comparison between the effective angular speed of the haptic device when the user interacts with it, and a simulation of the haptic model.

4.5. Redesigning the behaviour of the interface: testing, acquisition and technical specification quantification

Both the physics and high-level models have been validated, and experimental sessions with users have been performed in order to validate the reverse engineering process. Interacting with the iVP of the door, the users have been asked to describe their desired behaviour and thus experience it once the new one was rendered according to their indications (Figure 7). A number of behaviours have been identified as interesting. Two standard behaviours, that can be found in a number of commercially available similar products have been selected and used to validate the reverse engineering approach: an experience with very low friction and an experience where a damping effect reduces the speed of the door when it is being closed (usually known as 'soft closing').

To render these behaviours (for all of them an equivalent inertia of I = 0.36 kg m^2 is used for the haptic model), two impulses were used as external force: the magnitude of the first impulse is such as to allow the door to arrive at 90°, while the second one brings the door back to 90°- while in each test the magnitude varies, the function remains the same (Figure 8). For the optimisation, the dimensions of the mechanism are not changed. It is important to mention that the feasibility of adopting the parameters obtained from the optimisation into the real product is not considered.

4.5.1. Behaviour 1: low friction

In the first case, the haptic model has a friction force magnitude c_{at} = 0.1 N (Equation (15)), while all remaining parameters are zero. The comparison between the response of both systems (i.e. the haptic model and the physics one) as a function of time is illustrated in Figure 9. In Figure 10, it is plotted the angular speed of both systems as a function of the angular position: the system accelerates up to a certain speed, where it later decreases slowly, and then, when a new impulse is given, it reverses, returning to the initial position. We mention that choosing a value of c_{at} that is too low or zero makes the actual mechanism unable to reproduce the behaviour of the haptic model, hence there is a practical limitation on how low this friction value can be.

By observing Figure 11, it can be noted that the behaviour is preserved when all the parameters are within a margin of 10% from the original values.

4.5.2. Behaviour 2: damping when closing - soft closing

In the second case, the haptic model has: (1) a viscous damping $c_v^+ = 2$ Ns, that affects the dynamic system when the angular speed is positive (closing), after around 60°; (2) a global dry friction c_{at} = 0.1 N.

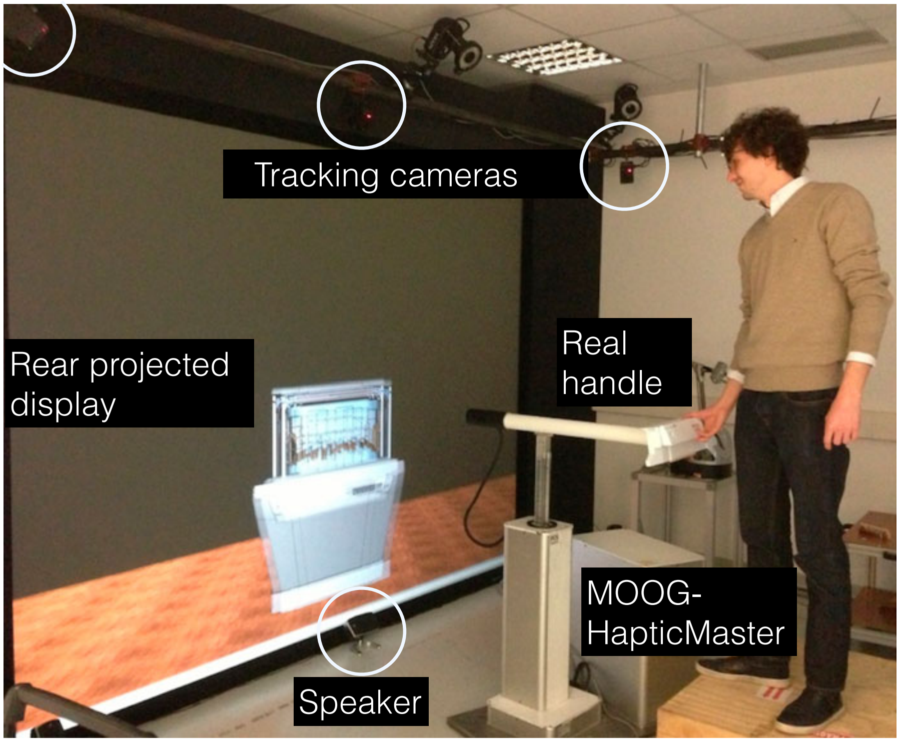

Figure 7. A user interacting with the virtual replica of the door of the dishwasher. The image shows also the multisensory set-up built: it consists of a rear projected display (www.cyviz.com); an optical tracking system (www.artracking.de); a 3DOF MOOG-HapticMaster device whose end-effector has been replaced with the real handle of the dishwasher; and a speaker placed behind the haptic device.

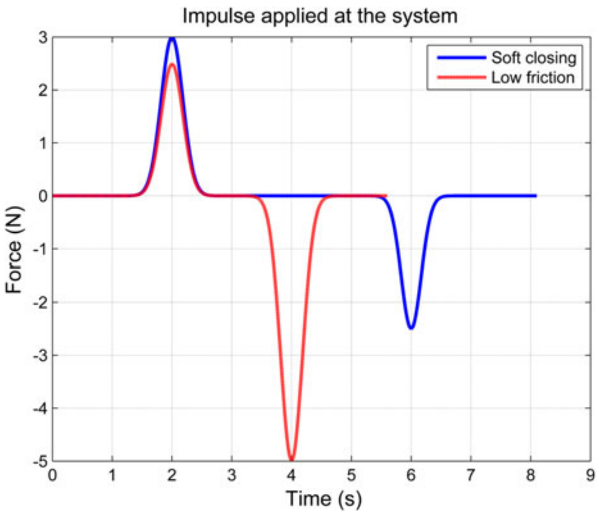

Figure 8. Force applied at the system, where the magnitude of the peaks are set so the angle goes from 0 to 90°, returning afterwards to 0. The image summarises the shape of the force for each behaviour rendered: low friction and soft closing.

Unlike the previous case, the haptic model and the dynamic system do not have such a good correlation (for the reasons discussed in Section 4.4), which can be observed comparing the time history of the speed (Figure 12) and the acceleration (Figure 13). The asymmetry between closing and opening is better illustrated by the speed as a function of the position (Figure 14).

By observing Figure 15, it can be noted that, after simulating the system changing all the parameters together, except the length of the links, the behaviour is preserved, when the parameters are within a margin of 10% from the original values.

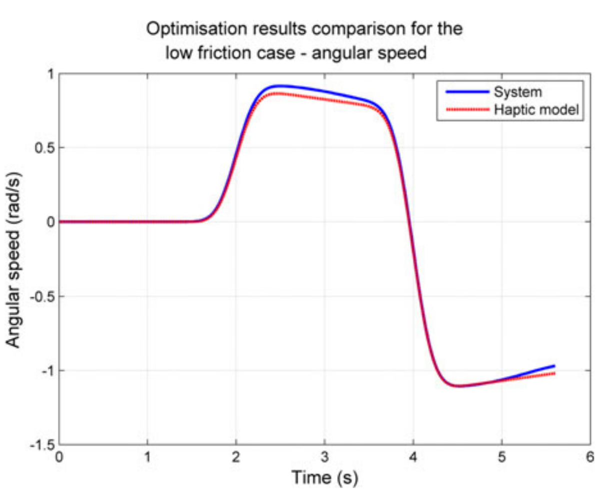

Figure 9. Comparison between the response of the haptic model and the result of the optimisation for the dynamic system, when very low dry friction is present.

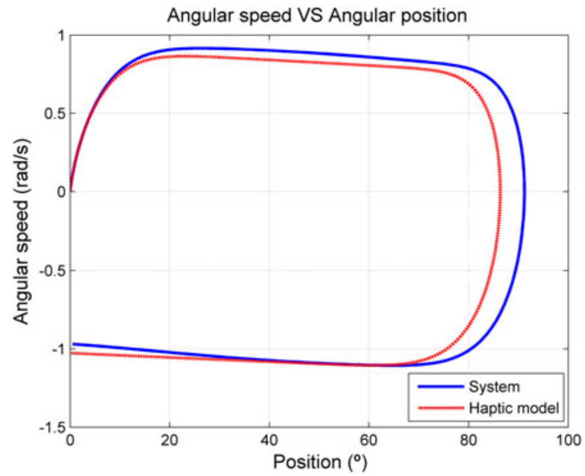

Figure 10. Comparison between the angular speed of the haptic model and the one obtained from the optimisation of the dynamic system, when very low dry friction is present.

5. Conclusion

This paper has proposed a method for guiding the redesign of the interfaces of products through a reverse engineering approach. The purpose of this approach is to give a technical foundation to the process of acquiring and transferring the insights coming from users into new product concepts. The method is grounded on the consciousness that nowadays, the design of new products has to be driven by an in-depth understanding and assessment not only of its technical performances but also of the positive multisensory experience the product should elicit when a user interacts with it. This means that an active involvement of the users themselves is necessary to properly understand what the desired experience to be designed is. The term 'reverse' underlines the awareness that

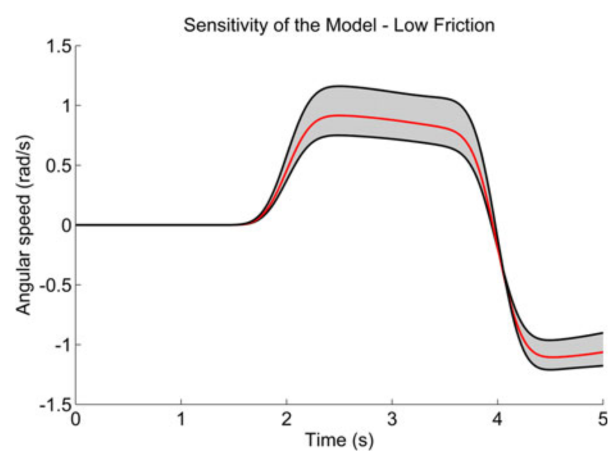

Figure 11. Effect of increasing or decreasing the values of all the parameters of the model together (except the length of the links) by 10% on the response of the system model for the low friction case.

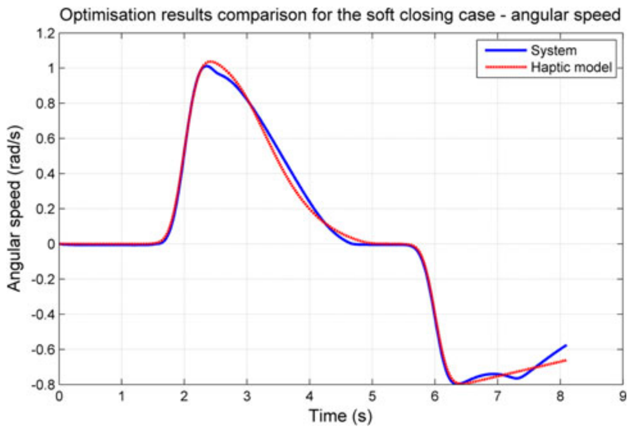

Figure 12. Comparison between the response of the haptic model and the optimised dynamic system, in terms of speed, when viscous damping is also present when the door is being closed.

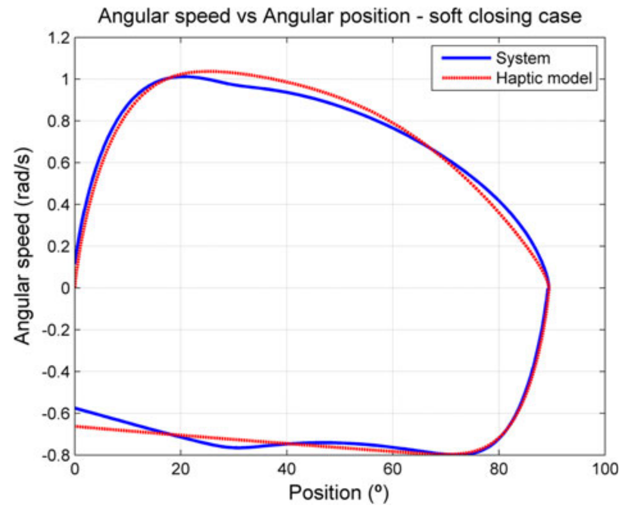

Figure 14. The asymmetry between the closing and the opening: the door angular speed as a function of its position.

in order to identify this desired experience it is necessary to start from a baseline one, which is not satisfying: capturing the gap between the current and the desired one gives clear indications to designers and marketing experts about how users' needs are evolving.

Based on this conviction the paper has explained why the product interfaces should no longer be seen merely as components of the product but as dynamic interactive systems: at a given user input they provide as output the system response. Then, the proposed reverse engineering approach has been discussed.

This approach has been conceived to provide practical indications on how to correctly model the physics behind the action-reaction effect and to demonstrate how it is possible to transform this model into a parametric and tuneable interaction experience to test. To this aim, interactive Virtual Prototypes are used to render the multisensory experience and let the user perceive it in real-time. The behaviour of these interactive Virtual Prototypes is controlled through a high-level model whose parameters can be changed to allow the user to perceive different kinds of interactions. The values of the parameters determining the desired behaviour can then be transferred into a physics model in order to extract technical specifications: these will be used by the designer to transform the desired experience into a physical artefact.

The redesign of the haptic feedback of the door of a dishwasher has been used as a case study for testing the validity and the effectiveness of the method in retrieving the necessary technical specifications for starting the activity of designing the desired behaviour of the door. To provide a more detailed

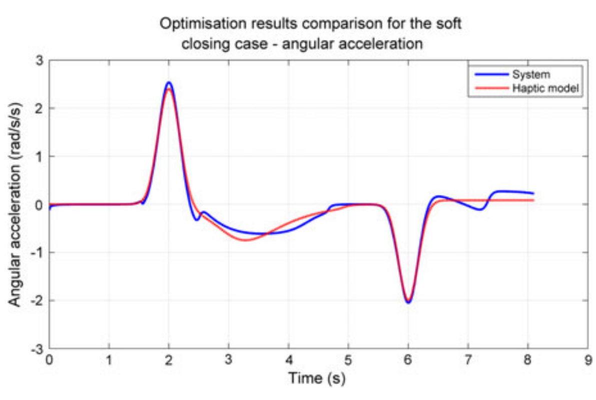

Figure 13. Comparison between the response of the haptic model and the optimised dynamic system, in terms of acceleration, when viscous damping is also present when the door is being closed. The shapes of the curves change significantly, possibly undermining the quality of the experience. This door behaviour is what is usually called soft closing.

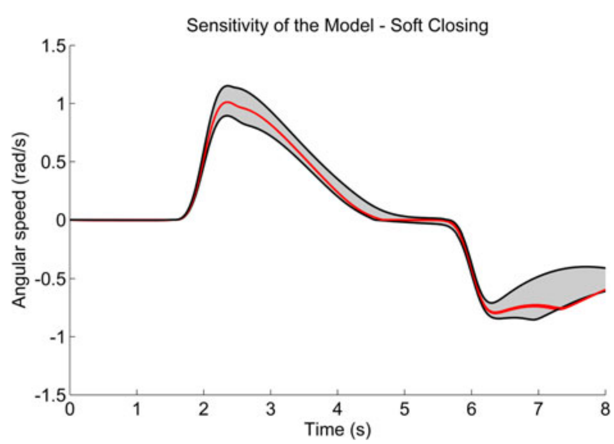

Figure 15. Effect of increasing or decreasing all the parameters of the model together (except the length of the links) by 10% on the response of the system model for the soft closing case.

discussion, in this paper two different behaviours have been described and their design parameters specified in order to demonstrate the validity of the approach in supporting the design activity of the interfaces of a product.

In discussing the limitations of this study it is worth underlining here that the quality of the multisensory scenario created has been influenced by both the performance of the devices used together with the way these and their behaviour have been adapted in order to render the interaction. Each tool has its intrinsic limits and by definition they are not transparent (e.g. the haptic device). Understanding these limits well in advance is a requisite for properly defining the boundary conditions of the analysis, and overcoming these limitations.

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