A Review of Virtual Prototyping Approaches for User Testing of Design Solutions

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ABSTRACT

The paper reviews the latest research on virtual prototyping approaches for user testing designs. The different approaches are compared and their usefulness are evaluated. Virtual prototypes are modifiable, allow each sensory channel to be manipulated separately and allow reuse of prototyping elements. Essentially, virtual prototyping could mean faster decision-making in product development processes than traditional physical prototyping. Three categories of virtual prototyping approaches are established and their strengths and weaknesses are discussed and illustrated through cases from literature. The categorization suggested are *Virtual Prototyping*, *Interactive Virtual Prototyping* and *Mixed prototyping.* Several studies show that virtual prototyping approaches can be useful and effective. Still, some challenges remain to be solved. The fidelity provided by today's haptic devices is not very high, and some studies received feedback from the users that the devices that needed to be worn was too intrusive. Current trends are combining both physical and virtual prototyping to meet the challenges of low haptic fidelity. Further, attempts at distributing virtual prototypes across networks to achieve more flexibility in the way designers interact with users show much potential.

KEYWORDS: Virtual Prototyping, Interactive Virtual Prototyping, PDP, User Testing, Multi-Sensory, Haptics.

1. INTRODUCTION

Making design-decisions more efficiently makes the product development process (PDP) more efficient and gives a competitive edge [1]. An increasing worldwide competition, in both developed and developing countries, is a strong incentive for companies to look for ways of making their PDP more efficient. Because of this, western industries are relying heavily on improving their design and development processes to keep their position in the market [2]. A powerful production strategy for meeting these challenges are the concept of mass customization [3]. Flexible computer-aided manufacturing systems have made it possible for companies to produce products customized to the individual user at almost the same cost as mass-produced products. A production strategy earlier limited to wearables and individual products are now being used in other product categories as well, for instance information appliances, mobile phones, home appliances and so on. Hence, the flexibility in capturing user feedback is now as important as ever.

A widely used and important method for designers to receive user feedback is prototyping.

A prototype is a purposeful draft version of a design, or parts of a design, that allows the designer to explore his ideas and communicate it to stakeholders and users for evaluation of the design [4]. Prototyping does usually occur in all stages of the PDP, with varying resolution [5]. A prototype can be made to test everything from aesthetic appeal to the quality of a technical solution, and can be anything from paper drawings to a fully functioning prototype of a car. The most essential reason for the importance of prototyping is that changes to the design made early in the process are much less expensive than changes made late [6] [7].

Prototyping for the development of industrial products has traditionally been physical prototyping [8]. Physical prototypes are physical representations of the design that are usually made of materials and parts that are easy to manipulate, so the construction time of the prototype becomes short. The disadvantages of physical prototyping are its high costs, development time and the limited flexibility once the prototype is made [9]. For these reasons, the use of virtual prototyping is highly interesting to the fields of engineering and industrial design. Virtual prototypes are easy to modify and thereby more flexible than physical prototypes. In addition, the time it takes to develop a virtual prototype (VP) can potentially be much shorter than a physical one, especially if the prototyping scenario allows re-use of earlier developed software. According to Bordegoni [10], companies that incorporate virtual prototyping in their PDP could reduce their material costs and production time.

The aim of this paper is to identify and discuss the status quo of virtual prototyping approaches for testing designs with users. User testing designs entails testing crucial features of the design with the future end-users of the product. Crucial features can be aesthetic, functional or both, depending on the design. Further, the different approaches are compared in terms of important factors in a PDP and what aspects of a design they are suitable for prototyping.

The paper is well suited to quickly give an overview of the latest research and research groups related to virtual prototyping. The important research questions are:

1. *Are virtual prototyping approaches mature enough to be useful for user testing in industry or are they still in their infancy?*
2. *What are the current main challenges for virtual prototyping approaches?*
3. *What are the future trends in virtual prototyping approaches?*

Three main categories of virtual prototyping approaches are suggested: *Virtual Prototyping, Interactive Virtual Prototyping* and *Mixed Prototyping. Virtual prototyping* gives the users a chance to evaluate the design with their vision and hearing. *Interactive Virtual Prototyping* allows the users to experience the prototype through haptics in addition to vision and hearing. While *Mixed Prototyping* is an approach where physical models are used in combination with virtual prototyping. The categories will be elaborated on in their respective sections.

The paper will start by explaining the methods used in the data collection and an overview of what materials that is reviewed. Section 3, 4 and 5 describes the three different main approaches of using virtual prototyping for design evaluation and discuss some of the latest research in each of them. Respectively, *Virtual Prototyping, Interactive Virtual Prototyping* and *Mixed Prototyping.* Section 6 discusses the application areas and compares the different prototyping approaches. Future trends are also discussed. Section 7 concludes the paper.

2. MATERIALS AND METHODS

The main bibliographic database that was used for this review paper was Elsevier's Scopus. As a supplement Google Scholar and Google search was used, especially when specific authors or titles that wasn't available through Scopus was needed. Access to the Scopus database was achieved through the Norwegian University of Science and Technology.

Keywords that was used in the search process was; *Virtual Prototyping, Interactive, Product Development, Virtual Reality, Design Evaluation, User Testing, Haptics.* Two main criteria were established for literature where the case-studies described were used to evaluate todays existing state of virtual prototyping approaches;

1. The literature must have been published after 2005.
2. The aim of the experiments in the case-studies must have been to evaluate design solutions with end users.

92 papers and book chapters were screened in terms of abstracts, 53 were screened in terms of content and 39 were included.

3. VIRTUAL PROTOTYPING

A virtual prototype (VP) is a computer simulation of a physical product that can be presented, analyzed and tested as if on a real physical model [11].

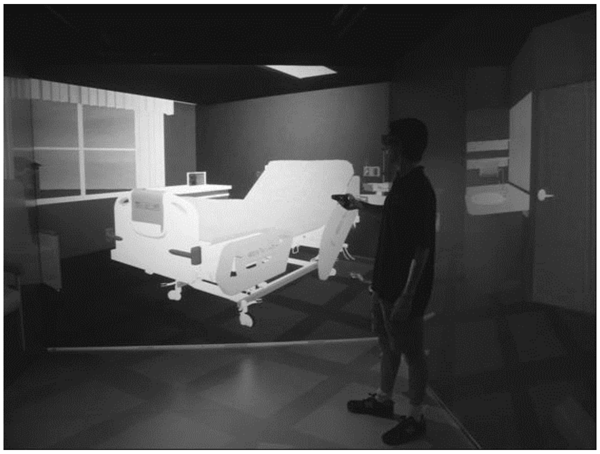
Ferrise [12] stated that a VP should fulfill these requirements:

- ***Realism.*** The VP should be a credible simulation of the physical prototype, hiding from the user the complexity of the simulations, and of the technologies at its basis.
- ***Sharable among different stakeholders.*** One interesting advantage of using virtual prototypes compared to physical prototypes is that they can be shared over the network and accessed by different stakeholders at the same time. This enables collaborative design and testing activities [10]
- ***Modifiable and parametric.*** One of the most important advantages of using virtual prototypes is that they are easily modifiable and can be even parametric. By using the physical prototype of an object, a person can only express an opinion as to whether he likes or dislikes it, but cannot easily test variants of the object. By using a parametric virtual model instead the user can ask to make changes of the prototype until an optimum has been reached.
- ***Context sensitive*.** The prototype should reflect the changes due to the context it is put in.

The next section will discuss three of the latest cases where the VP approach is used for design evaluation with users. The three cases were chosen because they are considered most successful by the author and they meet the main criteria described in section 2.

3.1 Recent Cases in Virtual Prototyping

Dunston [13] developed a virtual reality mock-up for reviewing the design of hospital patient rooms. A Cave Automatic Virtual Environment (CAVE) approach was used to create a full-scale, stereoscopic, real-time, 3D-visual simulation of the room design to allow a realistic investigation of the actual spatial relationships.



Critical aspects of hospital rooms such as clearances, sound levels, sightlines and functionality could be explored. Interacting with the virtual environment was also made possible by a handheld controller and enabled the user to grab things and carry them around to check if there is adequate space, and rearrange furniture within the room. Variables that are difficult to manipulate using traditional physical mock-ups was possible to manipulate, such as changing the overall lightning levels, the view from the window to simulate different heights in a building and the time of day.

The main challenges reported was the development time of the VP. Even though the feedback from the decisions makers at the hospital was positive and the price of the VP could reduce the total prototyping costs to one fifth, the hospital had to make decisions very fast and this was the main reason virtual prototyping wasn't utilized more. Future plans was to develop generic software libraries with standardized elements to substantially reduce the development time. On the other hand, Majundar [14] reported that the development time of their VP of a court room was one of the main benefits compared to physical mock-ups.

In Bruno [15] a system named VP4PaD (Virtual Prototyping for Participatory Design) was developed to evaluate product interfaces through allowing users to directly interact with a 3D model of the product interface. VP4PaD allowed the users to sketch the product interface by selecting and placing functional elements, such as buttons, handles, switches etc. The user was then able to create a fully functioning product interface, and very easily express their preferred interface. The setup is shown in figure 1 [15].

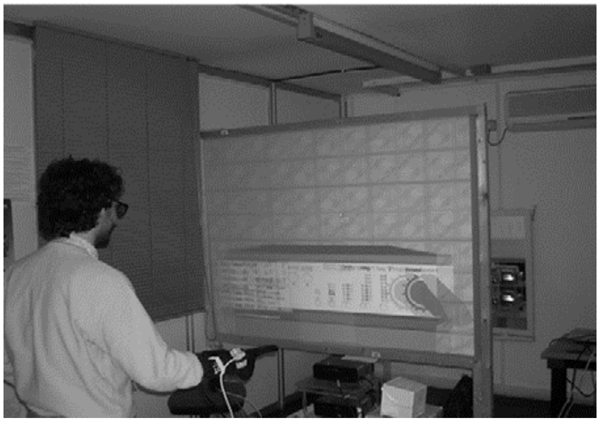


Figure 1: Sketching session.

Bruno [15] exploited the modifiable nature of a virtual prototype with several standard functional interface elements that were easy to position and adjust for the user. The modifiability allowed several design iterations to take place in the same session. The results showed that the redesigned interface had a better degree of usability than the commercial interface; both the number of mistakes and the task completion times were always the lowest when users used the redesigned interface.

The examples of virtual prototyping found in recent literature indicate that virtual prototyping is mainly used in evaluation of complex designs where developing an equivalent physical prototype would be very time consuming and costly. Still, the prototyping approaches reported in Dunston [13], Majundar [14] and Bruno [15] are at an experimental stage and not widely used in industry. It should be mentioned that the number of examples in literature where VP is used for evaluating designs is limited.

4. INTERACTIVE VIRTUAL PROTOTYPING

Interactive virtual prototypes (IVP) are prototypes made for a virtual environment and that allow the user to use several of their senses in the interaction with the prototype. The senses most focused on in literature are sight, hearing and touch, as these are the senses considered to be most crucial for design evaluations. A multi-sensory prototyping approach makes the interaction more natural and is especially important for products that are interactive in their nature. Interactive Virtual Prototypes differs themselves from traditional Virtual Prototypes which only allow the user to interact passively through their vision. Furthermore, for the user-testing with IVPs to be comparable with user-testing performed with physical prototypes, the interaction has to be as natural and realistic as possible [16]. A natural and realistic interaction involves enabling the same sensory modalities that would be involved in the corresponding physical interaction [17].

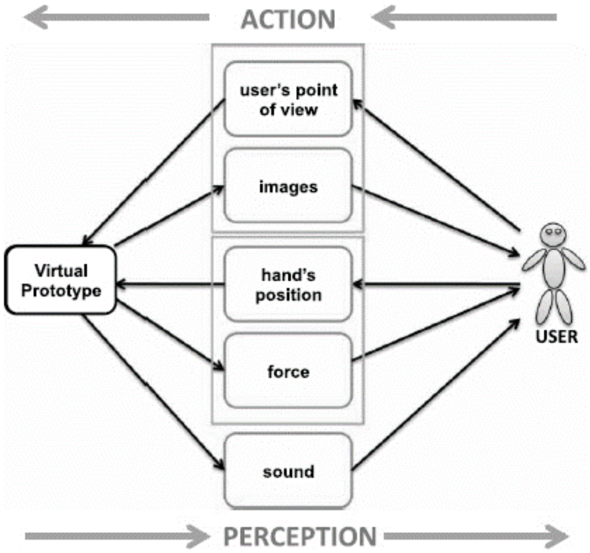


Figure 3: Diagram describing the correlation of user's actions and perception through the various sensory modalities [17]*.*

Ferrise (2013) has established certain requirements IVPs should meet when they are used for evaluation of designs with end users:

- ***Realism.*** The iVP should react to human senses exactly as a physical prototype, hiding from the user the complexity of the simulations, and of the technologies at its basis.
- ***Real-time feedback.*** The iVP should react to user's actions in real-time (from the users' perception point of view), with no perceivable delays (this impacts even on the realism of the simulation). It means that simulation algorithms should be fast enough to grant a real-time feedback. In case this is not feasible, simplified algorithms should be used. Simplifications should anyway grant the quality of the perception of the object. This implies that the problem moves from the simulation of the ideal physics-based behavior, to the simulation of the faithfully perceived physics-based behavior. It is highlighted that the most important aspect of the interactive Virtual Prototype is no more the complexity of the simulation of the product, but how the results of the overall simulation is perceived by the humans.
- ***Multimodality and multisensory.*** The iVP should involve the same sensorial channels and the same interaction modalities that are involved during the interaction with the real product. Since involving several senses means using dedicated devices for each sense, it has to be taken into account that perception might be affected by the device if it is not transparent, and that the sense of presence might decrease if the user does not feel to be into the virtual world because of the many and invasive devices worn [18] [19].
- iVPs should be based on:
  - ***Different functional models for each sense.*** Each sense should be treated separately from the other ones. This would allow us to simulate situations that are not possible with physical prototypes (for example, sounds not resulting from the exertion of specific forces on an object).
  - ***Different functional models for each external behavior to analyze and test.*** The interactive Virtual Prototype that will be used

for specific and distinct analyses, for example for ergonomic analysis, should be based on different functional models from that used for the emotional response analysis.

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

The next section will discuss some of the latest cases where the IVP approach is used for evaluating designs with users. The cases were chosen because they illustrate the concept of an iVP well and report important challenges of iVPs today that need to be addressed.

4.1 Recent Cases in Interactive Virtual Prototyping

In 2006, the research group of Bordegoni at Politecnico di Milano presented two iVPs in a paper published in the international journal *Computers & Graphics* [20]. Bordegoni and her research group have had a strong focus on virtual prototyping during the last decade. The research group has also been organizing Virtual Prototyping Summer School since 2009.

The paper presented the results of a research project named the VeRVE[1] (Virtual Reality system for Validation of Equipment controls) project [20]. The goal of the project was to learn more about the use of haptic interfaces to evaluate ergonomics of boards of control of virtual products. The iVP resulting from the project aimed at evaluating control boards used in cars and home appliances. These control boards consist usually of buttons, slide-bars and knobs, and have traditionally been designed based on experimental data for parameters like optimal distances between commands, dimensions for the human hand and movement range etc.

Bordegoni [20] developed a 1 DOF active mechatronic system that exerted torques suitable for the simulation of knob controls. The system was tested by integrating it into virtual simulators of a car dashboard and a washing machine and allowed the designers to evaluate the behavior, usability and ergonomic aspects of the knob. The system was tested by users and received positive feedback on the level of immersion and the realism of the haptic rendering of the knob.

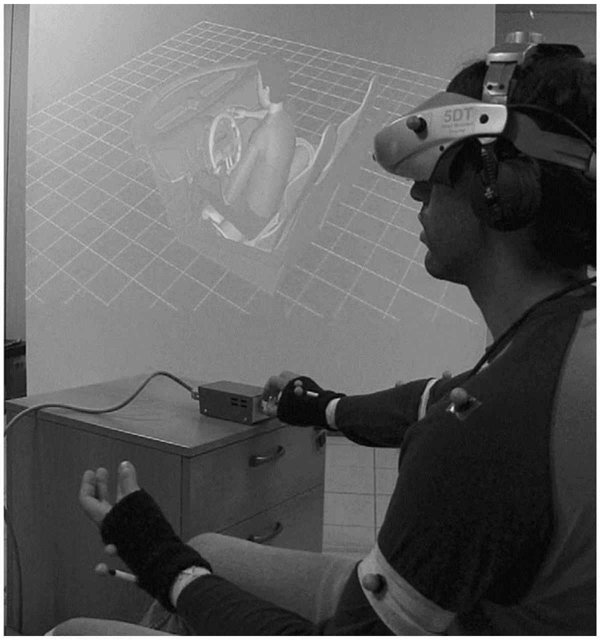


Figure 4: Usability testing of a knob in a car dashboard [20].

In Ferrise [21] a design evaluation with an iVP of a washing machine from Whirlpool[2] was performed. A physical machine was replicated as accurately as possible in an iVP, including possibilities of interacting with its moving components.

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[1] VeRVE project: www.media.unisi.it/verve.

[2] www.whirlpool.com

Figure 5: Design evaluation with iVP of washing machine with haptic device [21].

Two different tests was performed by ten users. The first test compared the realism of the iVP with the real machine, considering these aspects:

1. Haptic response of buttons
2. Knob click-effect
3. Knob torque
4. Door weight
5. Door click-effect when closing
6. Drawer weight
7. Drawer click when closing

The results from the first test highlighted challenges that have been found throughout the literature review; todays existing haptic devices have problems realistically replicating the haptic response of the product [5] [17] [22]. However, the response appeared sufficiently realistic to be applicable in many design review contexts [7] [12]. Still, this area has potential for improvement.

The second test aimed at exploring how different sounds would influence the users' perception of a particular information. Three sounds were rendered for the users to represent the click-effect of the drawer. The user then had to select the one they would prefer to have in a real washing machine.

One of the interesting results from the test was that the users perceived the force of the clicks differently when matched with different sounds. This indicates that similar 'illusions' can improve the realism of future iVPs when technological limitations make it difficult to render the iVP realistic enough [23]. The results from the last test also demonstrates how sensory modalities focusing on sound can be evaluated with iVPs.

The research group at Politecnico di Milano used the same iVP again in 2013 to conduct a more thorough design evaluation with the model [17]. When interacting with the iVP, the user could use simple sentences to request a change in the model. For example: stronger force, higher click tone, more clicks.

All users considered the interaction with the iVP effective, especially to be able to physically touch the object. The users also thought the iVP was engaging and appreciated the opportunity of adjusting the iVP to suit their preferences. The same is also reported in Bruno [15], Ferrise [9] and Bordegoni [24]. Major issues was in terms of realism in the use of the end effector of the haptic device. The shape of the end effector was generic and compromised the realism of the iVP. This issue has been successfully addressed with customized end effectors in Graziosi [22] for an iVP of a dishwasher and in Bordegoni [25] for an iVP of a refrigerator door.

The literature shows that as the number of sensory modalities increase, as in iVPs compared to VPs, the complexity of the features that can be tested and the modifiability of the prototype decrease.

5. MIXED PROTOTYPING

Mixed prototyping is an approach were a combination of both physical and digital mock-ups are used with augmented reality techniques to simulate the relevant features of the product to the user. The modifiability is restricted to the virtual component, however the physical component contributes with a more realistic user experience, usually in terms of haptic modalities. A mixed prototyping approach should be preferred when the technologies, both hardware and software, are not able to reproduce all the information in a sufficiently realistic way [12].

The next section will discuss some of the latest cases where the mixed prototyping approach is used for evaluating designs with users. These cases were chosen because they are good examples of the typical techniques used in mixed prototyping, which is accurately covering a physical model with a 3d model and then displaying it through a head mounted display. The cases are also considered to be the most successful ones by the author and illustrate well the advantages and disadvantages compared to the other prototyping approaches.

5.1 Recent Cases in Mixed Prototyping

Aoyama [26] describes two successful prototypes for information appliances based on mixing interactive virtual prototyping and very simple physical mock-ups. Two simple physical shapes was made for a digital camera and a cell phone and covered with a virtual model that was displayed to the user with a video see-through head mounted display. The mixed approach allowed the users to touch and operate the prototypes as if they were real models. Figure 6 shows the virtual model (a), the physical model (b) and the mixed prototype (c).

Through magnetic sensors and a data glove the handling of the prototyped could be precisely tracked. Combining the tracking results with the results of a questionnaire survey, where users had to perform certain button sequences and evaluate the operability of the sequences, enabled the team to quantify the operability and designability of each button with a regression equation. The sum of the values for all buttons gave the operability of a whole user interface a score. Experiments later confirmed the effectiveness of the operability value for the user interface. Four different interfaces for a digital camera were evaluated by the regression equation and by test subjects.

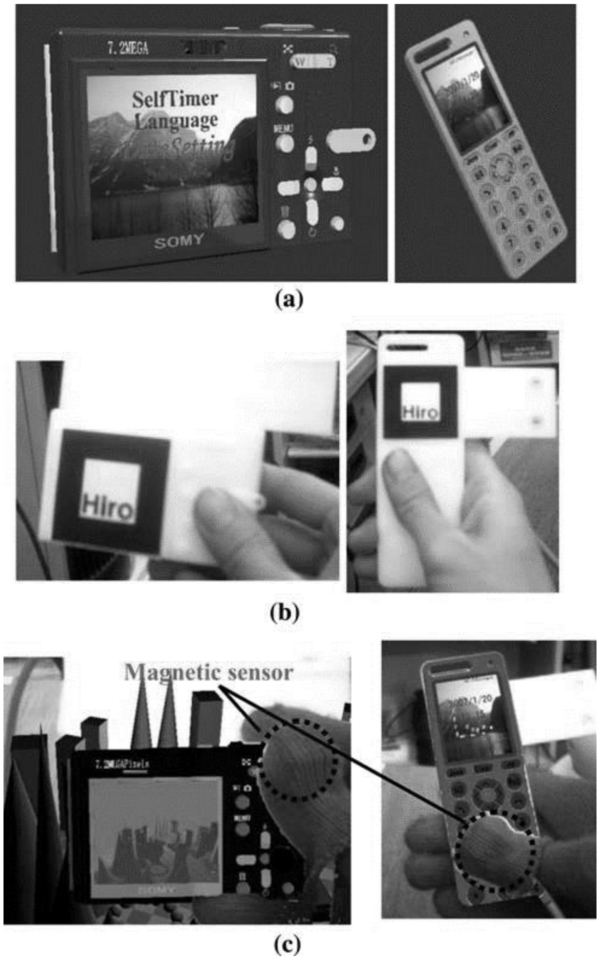


Figure 6: Three kinds of models. a) virtual model, b) physical model, c) mixed prototype [26]

The research presented in Aoyama [26] shows the potential of quantitatively collecting data with high precision from a prototype with interactive virtual components and using it to evaluate designs. An approach such as this would not work with a pure physical prototype [27].

A mixed prototyping approach was also used in Bordegoni [28] in the development of a prototype of a washing machine. A physical model with a control knob was made with simple building materials and rapid prototyping techniques. Further, a highly realistic visualization of the appearance of the washing machine was created and displayed covering the physical model. The knob was programmable and specifically customized for this application, and could be programmed directly during testing. Figure 8 shows the prototyping setup.

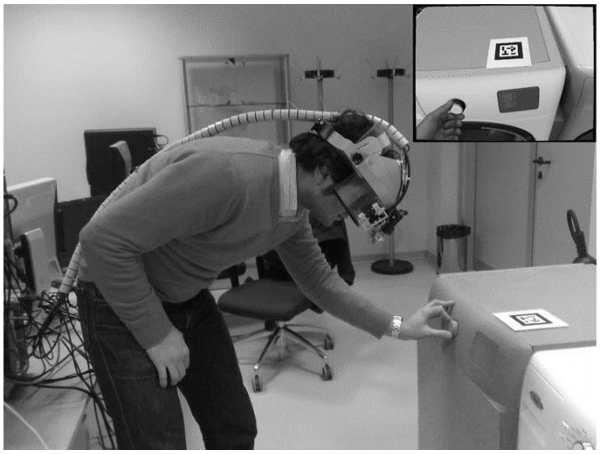


Figure 8: Virtual washing machine based on MR techniques [28].

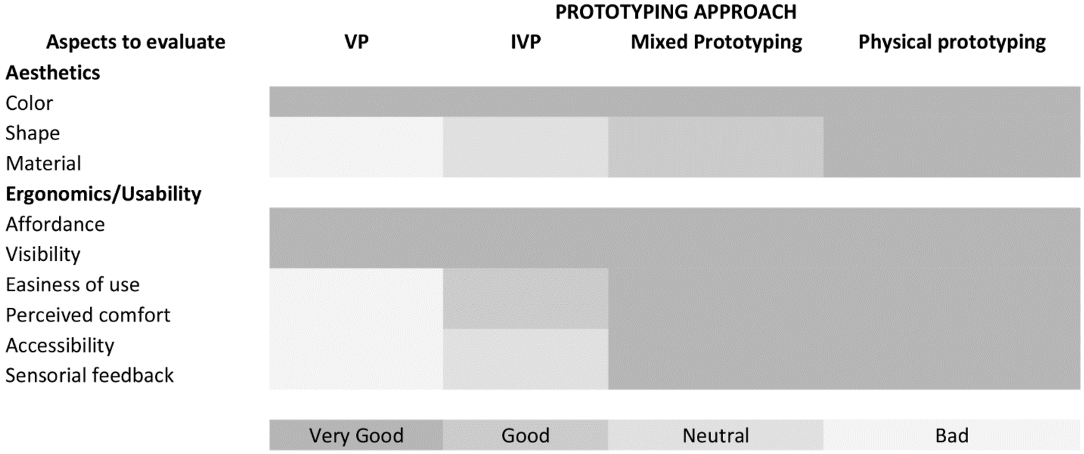
The user was able to test a realistic representation of the washing machine super-imposed onto the physical model, seen through the head mounted display. The mixed prototype allowed the user to operate the physical knob for changing the washing program as well as request a change in the haptic response of the knob.

In the experiment, the mixed prototyping approach made it easier to provide a higher level of fidelity in the haptic modality than an iVP would have. The reason is that including a physical mock-up of the product gives the prototype a more realistic shape and allows the user to touch the prototype directly with his own hands. In contrast, the iVP developed in Ferrise [21] allowed the user only to interact with the prototype through a generic end effector attached to the haptic device. However, the complexity of the testing situations in the iVPs was higher than in the mixed prototypes. Further, the mixed prototypes were not as modifiable as the ones with more virtual components.

The results from testing the mixed prototype with users confirmed it was effective, as well as engaging and attractive. Nevertheless, a major issue that was raised was the intrusiveness of the head mounted display, as well as limitations for field of view and range of motion. Similar issues are raised in Witmer [18].

6. DISCUSSION

To further explore the usefulness of virtual prototyping it is interesting to consider what information is needed to evaluate certain aspects of a design and compare with what information each virtual prototyping approach is suitable for providing. Table 1 summarizes the findings of the literature review and gives an indication on how suitable the different approaches are at evaluating different aspects of a design.



	PROTOTYPING APPROACH			
Aspects to evaluate	**VP**	**IVP**	**Mixed Prototyping**	**Physical prototyping**
Aesthetics				
Color	Very Good	Very Good	Very Good	Very Good
Shape	Bad	Neutral	Good	Very Good
Material	Bad	Neutral	Good	Very Good
Ergonomics/Usability				
Affordance	Very Good	Very Good	Very Good	Very Good
Visibility	Very Good	Very Good	Very Good	Very Good
Easiness of use	Bad	Good	Very Good	Very Good
Perceived comfort	Bad	Good	Very Good	Very Good
Accessibility	Bad	Neutral	Very Good	Very Good
Sensorial feedback	Bad	Neutral	Very Good	Very Good

Very Good	Good	Neutral	Bad

Table 1: How suitable different prototyping approaches are at evaluating common aspects in a design evaluation.

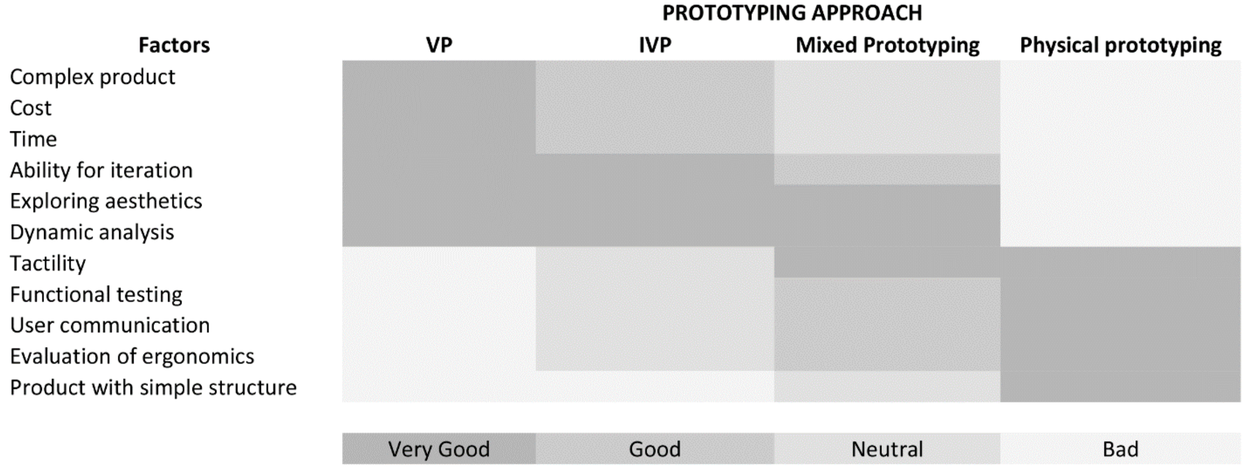
The findings of the literature review shows that what aspects of a design each prototyping approach is suitable for prototyping is closely linked to what sensory modalities each approach can provide. Virtual Prototyping only allow interaction through vision, and is thus primarily suitable for evaluating aspects only relying on vision, such as color, affordances and visibility. IVPs also include haptic modalities which allows the user to better evaluate aspects such as usability and comfort. Mixed prototypes are suitable for most aspects, however the fidelity of the shape and the material is rarely as high as it would be if a physical prototype would be used.

Nevertheless, there are often more factors than product features to consider when a prototyping approach needs to be chosen. Liu [27] argues that virtual prototyping are best suited for situations where physical prototyping is impractical, impossible or inefficient, while Grimm [29] emphasizes that physical and virtual prototyping are not competitive but complementary technologies. In Campbell [30] it is also stated that physical and virtual prototyping are two valuable techniques that should be joined together to form a powerful prototyping tool for complex products. Table 2 takes a broader view on the PDP than table 2 and highlights the strengths and weaknesses of the different prototyping approaches in terms of important factors in a PDP.

It is clear from the literature findings that complex products are costly and time consuming to prototype physically. For complex products, digitally modelling and programming the prototypes are faster than building them physically, especially if re-use of the model or parts of it is possible. Digital models are also easier to modify than physical ones. However, for simple products or products where high fidelity of the ergonomics and functionality is necessary, a physical prototype is the better choice.

Each PDP is different and have different priorities and boundaries. Regardless, there are most likely potential for improving efficiency in many PDPs if the optimal prototyping method is chosen.

The current main challenge are the fidelity of the haptic feedback. Visualization and sound technology has developed fast the last decades, while haptic have not [31] [22] [15]. Today's haptic devices aren't able to provide very realistic force feedback without highly customizing the haptic device, and even less tactile feedback from shapes [32] [33]. However, for many testing purposes medium fidelity is considered sufficient to get the necessary feedback from users [28].



	PROTOTYPING APPROACH			
Factors	**VP**	**IVP**	**Mixed Prototyping**	**Physical prototyping**
Complex product	Very Good	Good	Neutral	Bad
Cost	Very Good	Good	Neutral	Bad
Time	Very Good	Good	Neutral	Bad
Ability for iteration	Very Good	Very Good	Good	Bad
Exploring aesthetics	Very Good	Very Good	Very Good	Bad
Dynamic analysis	Very Good	Very Good	Very Good	Bad
Tactility	Bad	Neutral	Very Good	Very Good
Functional testing	Bad	Neutral	Good	Very Good
User communication	Bad	Neutral	Good	Very Good
Evaluation of ergonomics	Bad	Neutral	Good	Very Good
Product with simple structure	Bad	Bad	Neutral	Very Good

Very Good | Good | Neutral | Bad

Table 2: Strengths and weaknesses of each prototyping approach in the PDP.

6.1 Further Trends

The literature that was found describing pure virtual prototyping for design evaluations tends to direct itself towards more complex designs, usually in terms of scale, such as interior design, room design and architecture, however the amount of literature is limited [34] [13] [14].

Another exciting trend is the exploration of the potential of digital prototypes distributed across networks. In Bordegoni [35] two setups for a car interior were created at two different locations, one for the designers and one for the users. The designers were then able to get user feedback from the users at the other location and make changes to the design in real-time, hence saving crucial decision-making time. The same distributed approach was successfully used in Tuikka [36] and Nan [37].

Further, an interesting future possibility for virtual prototyping is the commercialization of virtual reality and augmented reality technologies, such as Oculus Rift[3] and Microsoft Halo[4]. Together with standardizing libraries for software elements used in virtual prototypes these technologies could allow designers to test their virtual prototypes very quickly on many users in different countries and age spectrums. It will also become substantially easier for the general public to create their own VPs.

5. CONCLUSION

Several studies have been presented throughout the paper where virtual prototyping approaches have been considered useful and effective for design evaluation. In one study the virtual prototype was also used to re-design the interface of a washing machine which showed itself to improve usability, both compared to the original user interface and to the interface of a washing machine already on the market. Still, no literature has reported that virtual prototyping approaches are being widely used in the industry, which confirms the preconceived perception that virtual prototyping approaches are still in their infancy.

Two main challenges for today's virtual prototyping approaches have been identified; the fidelity of the haptic feedback given to the user through todays haptic devices is not very high, and the devices needed to worn by the users during experiments can be very intrusive.

There are several exciting trends in virtual prototyping currently. One is the attempt of joining together the two approaches of virtual and physical prototyping and extracting the best features from both. This is called mixed prototyping and is a response to the current limitations that exist in available haptic devices. Another exciting trend is distributing the digital prototypes across networks. Hence, allowing designers to get feedback from users in different locations and settings in real-time.

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[3] https://www.oculus.com/

[4] http://www.microsoft.com/microsoft-hololens/en-us

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