Lawson, Glyn and Salanitri, Davide and Waterfield, Brian (2016) Future directions for the development of Virtual Reality within an automotive manufacturer. Applied Ergonomics, 53 (B). pp. 323-330. ISSN 0003-6870

The future of Virtual Reality in the automotive industry

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Abstract. Virtual Reality (VR) can reduce time and costs, and lead to an increase in quality, in the development of a product. Given the pressure on car companies to reduce time-to-market and to continually improve quality the automotive industry has championed the use of VR across a number of applications, including design, manufacturing, and training. This paper describes interviews with 11 stakeholders from an automotive manufacturer about their current physical and virtual properties and processes. The results guided a review of research findings and scientific advances from the academic literature, which formed the basis of recommendations for future developments of VR technologies and applications. These include: develop a greater range of virtual contexts; use multi-sensory simulation; address perceived differences between virtual and real cars; improve motion capture capabilities; implement networked 3D technology; and use VR for market research.

Keywords

Automotive; human factors; Virtual Reality

Introduction

In the automotive industry the development and application of new technologies is a key factor for success in an increasingly competitive market that requires faster time-to-market and ever higher quality of products (Choi and Cheung, 2008; Lawson, Salanitri and Waterfield, *In press*). Virtual Reality (VR) has been seen as one of the technologies that can help achieve these aims (Mujber et al., 2004). VR is a system which permits users to interact, move, look at, and be immersed in a 3D environment (Rheingold, 1991). In the automotive domain, VR has resulted in benefits in several applications. These are described in the following paragraphs.

Design. Car design is a process requiring continuous modification and reviews, with the necessity to revert to previous decisions several times before the car finally reaches production (Fiorentino et al., 2002). This characteristic has been seen as one of the most expensive and time consuming aspects of the process. Indeed, as Gomes de Sá and Zachmann (1999) stated, the early design phases can impact on up to the 70% of the total cost of a product. In this scenario, VR can reduce cost and time by replacing physical mock-ups with virtual ones (Shao et al., 2012). This can support simplification of the review process by avoiding the rebuild of physical mock-ups in case of design errors or changes (Kim et al., 2011). Moreover, VR can be used for design and evaluation during an early stage of the development process, before expensive and time-consuming physical mock-ups are produced (Lawson and Burnett, *in press.,* Lawson et al., 2015). Another utility of VR in design is the possibility of having multidisciplinary teams and teams spread across the world, to work together on the same prototype at the same time (Mujber et al., 2004). Regarding this, Lehner and DeFanti (1997) tested distributed VR for large vehicle (i.e. loader) development, demonstrating a cost-time reduction and quality increase.

Virtual Prototyping (VP). As a sub-section of *Design*, Virtual Prototypes are in some instances used to replace physical mock-ups. With recent progress in the capabilities and development of software and hardware, VR can replicate physical models allowing for a drastic cost and time reduction derived from the avoidance of building physical mock-ups (Kulkarni et al., 2011). Moreover, in the decision making process, VP can simply procedures and avoid the so called "bottleneck effect" (Fiorentino et al., 2002) which manifests from errors in the early stages of a component's development and constant reviews, leading to the necessity of rebuilding physical mock-ups. With VR this effect could be avoided with the possibility to modify a VP in real time.

Manufacturing. The application of VR to manufacturing is called Virtual Manufacturing (VM). VM has been defined as the use of VR or computers for the development of a product (Shukla et al., 1996). The advantages of VM range from the improvement of the decision making process to cost reduction (Mujber et al., 2004), to the enhancement of risk measures and control of manufacturing processes (Lee et al., 2001).

Virtual Assembly (VA). Related to VM, VA permits the assembly and disassembly of virtual objects (Qiu et al., 2013). VA allows the evaluation of worker's well-being and health and safety measures due to the possibility of creating virtual representations of workplaces. Jayaram et al. (1997) observed that VA gives an enormous advantage in the process of design and new tool implementations in improving product quality and reducing time-to-market.

Training. Borsci et al. (2015) demonstrated that mixed reality training of automotive service operations is preferred by trainees over traditional observation-based approaches. Moreover, studies have shown that with simulated training, task completion is improved over training on real equipment from the 50th percentile to the 66th (Stone, 2001). Furthermore, as Borsci et al. (*under review*) demonstrated for assembly and disassembly tasks, the retention of information after two and four weeks is higher for participants trained with VR than with other systems.

Given these benefits of VR to the automotive industry, several automotive OEMs are currently investing in the development and implementation of VR products. One example of this is Jaguar Land Rover (JLR), a highly successful vehicle manufacturer who sells vehicles in over 170 countries around the world. Their design and engineering headquarters in Warwickshire, UK hosts the Virtual Innovation Centre (VIC), a world-leading centre for VR technologies for automotive applications. Examples of some of the VR technologies already implemented at JLR are: A Cave Automatic Virtual Environment (CAVE) with high performance hardware and photorealistic software, a Powerwall, and a marker-based body motion tracking suit for ergonomics investigations. However, due to a continuous increase in the quality of VR systems, and the progression of knowledge around human factors of their use, a review was conducted to identify new opportunities in the field of VR for automotive applications. The review, reported in this paper, encompasses interviews with JLR stakeholders to identify issues with existing properties and processes, an analysis of the issues and new opportunities for the firm, a literature review on the human factors of VR in automotive and relevant related applications, and finally the creation of a set of recommendations for developing existing systems at JLR and implementing new technologies. A summary of early results was published in Lawson, Salanitri and Waterfield *(In press)*; this paper reports on the full review upon completion of the work.

Thus, the review was constructed of the following three phases which form the structure of this paper:

1. Interview with stakeholders
2. Analysis of issues and opportunities
3. Literature review on relevant studies in VR applications

Thereafter a set of strategic recommendations are made for developing VR technologies for automotive applications. While this review was commissioned by JLR, the recommendations are likely to be applicable across other automotive companies. The findings are also likely to be applicable to other industries (e.g. defence, aerospace, rail) in which ergonomics assessments are conducted as part of an engineering development process, with pressure to minimise the costs and time associated with physical prototype evaluations or the late identification of issues.

Interviews with stakeholder

Participants

A total of 11 JLR employees were recruited for the interviews. The participants were recruited from a variety of engineering functions with an average of 6.8 years in their current role (SD=6.6) and of 16.1 years at JLR (SD=13.7). All participants were approached by the researcher based on recommendations from the VIC of people who are currently using VR or who have expressed interest in using VR as part of their processes.

Materials

A questionnaire was developed to understand interviewees' roles, current processes and usage of vehicle properties (both physical and virtual). They were asked when properties were used within the vehicle development processes. Stakeholders were also asked which aspects of human interaction with the vehicle are necessary for their design and engineering activities. The questionnaire was divided into 12 topics gathered in 2 categories (Table 1).

Procedure

Participants were invited to a private meeting room. They were asked to read a participant information sheet and sign a consent form. The researcher explained the purpose of the study before asking questions about VR use in a semi-structured format. The study received approval from The University of Nottingham Faculty of Engineering Ethics Committee.

Table 1. Division of topics and categories derived from the questionnaire

	Categories	
Topics	**Physical Properties**	**Virtual Properties**
	Current use of physical properties Including which properties are currently used, their purpose (e.g. design, evaluation, communication), and use within the vehicle development process.	Currently used virtual processes / properties (examples as for *Physical Properties)*.
	Important attributes to be demonstrated on physical properties, e.g. appearance of the vehicle, exterior road scene, noise, reach/clearance, movement, vibration, touch or other.	Important attributes for virtual properties (examples as for *Physical Properties*)
	Limitations of physical properties/processes	Limitations of virtual properties/processes
	Users of physical properties (e.g. external customers, internal customers, seniors), from what perceptive are they used (e.g. assembly operator, customer, engineer) and how many users are typically involved in any activity.	Users of virtual properties (examples as for *Physical Properties*)
	Whether comparisons of alternative design proposals are an important part of existing processes and if so, what properties are used for these?	
	Whether reviews of competitor cars are part of the development process, and if so, when and how does this take place?	

Analysis of issues and opportunities

The outcomes of the interview analysis are summarised in table 2 below.

Table 2. Summary of the information extrapolated from the interviews

Topic	**Summary of responses**
Physical properties	
Current use of physical properties	Respondents use a variety of physical properties in their current processes, including a range of prototype vehicles and adaptations to donor vehicles (i.e. modified existing production cars). Physical properties are used for: evaluation of design intent with engineers and customers (internal employees representing customers, and external customers); design; communication (with engineers); and training of production line operations. Physical properties are used throughout the development process.

Important attributes to be demonstrated on physical properties	The most important attributes for physical properties are the appearance of the vehicle, sound/noise, ability to study reach and body part clearance, the visibility of an exterior road scene, and the evaluation of gross motion tasks. Moreover, haptic (or touch) feedback is important for certain applications, e.g.: detecting clashes during assembly or disassembly tasks; entry and exit studies to investigate body-vehicle clash conditions; studying reach to switches.
Issues with physical properties	The issues with physical properties are listed below: - The production, and therefore evaluation, of all vehicle variants (e.g. all pedal configurations, manual/auto, left & right hand drive) is impossible. - Sometimes a component evaluation has to be done out of context (e.g. evaluation of a steering wheel at a desk, rather than in a vehicle) - The evaluation of some aspects (e.g. electric features) have to wait until driveable vehicles are available i.e. late in the development process - The time to produce a physical property is long and therefore could slow down the entire review process. - The assessor's focus can be different when conducting evaluations on static vs. dynamic properties *{note: not all physical properties are driveable}* - Physical properties are difficult to alter - Physical properties take a lot of space - Getting hold of competitor cars is expensive - If physical properties are not produced, it can result in late changes to design intent i.e. issues are found late in the development process - Material type and forces may not be accurate i.e. for production line investigations - Manufacturing assessments may not be done in context (i.e. in the context of a moving assembly line/factory floor) - When assessing design intent using donor vehicles, there are likely to be differences to design intent; therefore debates occur around their representativeness - During vehicle evaluations with customer representatives, risk of damaging the vehicle property, or getting dirty, can affect users' interactions with the car. - The quality of the property can affect customers' feedback i.e. they cannot see beyond the fact that it is a buck. - Clay properties are difficult, expensive and time consuming to ship; they can cause problems with customs and require high secrecy.
Users of physical	Usually experts or seniors (for review); also internal employees (representing customers) and external customers.

properties	
Virtual properties	
Currently used virtual processes / properties	The three main technologies used at JLR are Cave Automatic Virtual Environment (CAVE), a dynamic simulator and a motion capture suit. However, desktop CAD use is ubiquitous amongst engineers. VR is used mainly: - To experience the vehicle architecture - To assess vision - To gain a perception of a surface move (i.e. to obtain a subjective experience of a geometry modification) - To study access to tanks containing fluid - For design evaluations - To calibrate perception (i.e. demonstrating design intent before experiencing a prototype vehicle which may not represent design intent exactly) - For motion capture of manufacturing tasks - For reviews of driving position - To solve issues during stakeholder reviews - To evaluate noise characteristics - For overlaying vehicle geometry (desktop) - For ergonomics analysis on desktop simulations Virtual properties tend to be used earlier in the process than physical properties, or if there is no physical property available
Important attributes for virtual properties / processes	Generally the same as for physical properties.
Limitations of virtual properties	The issues with virtual properties included: - Problems with depth perception in VR, mainly for short distances - A lack of weight indicators, haptic feedback and simulation of torques (particularly for manufacturing investigations) - Reach, clash/collision, sound and vibration feedback are missing. - Lack of reliability in hand motion tracking for ergonomics investigations. - Issues with the comfort of the body motion tracker suit (ergo suit) and difficulties and time required to put it on. - The colours of CAD parts in the virtual environments can affect perception. - Logistic problems were reported, for example travel time to different sites to the location of the VR systems. - Lack of fluid / flexible part simulation
Users of virtual	All properties were used by JLR experts. Virtual properties are sometimes

properties	used for demonstrations to seniors. A small number of procedures involve customers.
Across physical and virtual processes/properties:	
Comparisons of alternative design proposals	Most interviewees compare design alternatives, either alternatives for the current programme or make comparisons with outgoing models / competitors.
Comparison to competitors	This is done using scan data, photographs of cars, competitor benchmark data, or having properties sitting next to a representation of the design intent.

Table 1 summarises the interviewees' opinions towards physical and virtual properties used at JLR. The list of issues with physical properties justifies the advancement of VR-based processes; the majority of issues reported could be addressed with validated virtual properties and processes. Considering the emergent themes arising from the problems reported with existing VR technologies[1], it is possible to observe that issues exist related to image quality and characteristics in VR. In fact, issues with depth perception have been identified *(hard to judge space around your head)*, mainly regarding near distances. This led to one participant describing the "*perceptual calibration*" necessary when setting their driving position in the CAVE. The quality of colours was also criticised as the *garish colours* of CAD parts were reported to affect perception in VR.

The participants highlighted a lack of sensory feedback, such as touch feedback, including vibration and haptic feedback (*want physical feedback of manipulating parts for example testing to see if the pedal box can be fitted. It takes ages on a desktop*). Indeed, touch is important for the manipulation of objects and clash/reach detection (a limitation was reported as: *lack of* f*eedback on position, for example … for when I've touched something)*. In addition, the perception of weight *(Can't feel the weight of a tool as they're virtual)* and the simulation of torques were lacking.

Olfactory feedback and auditory feedback were also noted deficiencies with existing technology. Smell could be advantageous for assessing air quality (i.e. identifying foul smelling components) and marketing (*simulating the smell of a new car*), and sound could allow the evaluation of car/engine noise, switch noises, and manufacturing "clicks" when components are assembled.

Other issues concern accessibility to the technologies (*Have to book VIC and it's not always available; can't easily pick up kit and run; the event is not portable*). In fact, JLR has several sites, and it is not always efficient for users to travel to the site at which the technologies are located.

In the interviews new opportunities emerged. For example, the stakeholders suggested that the CAVE could be useful, and developed, for simulation of driver distraction studies during Human Machine Interface (HMI) development *(Needs interaction with other cars, people, roundabout)*. Moreover, a moving scene could enhance the sensation of driving *(Moving scene is needed for the subjective experience of a {vehicle} package)*. Others suggestions were made regarding opportunities for training assembly line operators, market research with VR and fluid simulation with VR.

[1] In this paragraph, the text in italics is taken from notes made during stakeholder interviews.

Literature review of VR applications

The interview results guided a literature review for possible solutions and other opportunities to enhance existing VR equipment for automotive applications. The findings are summarised in this section, categorised by topic.

Depth Perception. As said before, the interviews revealed issues with depth perception when using the VR technologies. Murgia and Sharkey (2009) demonstrated that rich virtual environments with textured background surfaces decrease the underestimation of depth presence. Hu et al. (2000) found that the ability to judge contact between objects in VR was improved using shadows. Moreover, multisensory environments have been found to increase depth perception, for example Swapp et al. (2006) & Bouguila et al. (2000) demonstrated that the addition of haptic feedback (to vision) enhanced depth perception.

Haptic and force feedback. It is well established within the ergonomics discipline that muscular effort and physical stress can lead to discomfort and injuries (e.g. back pain, Haslegrave and Corlett, 2005) and upper limb disorder (McAtamney and Corlett, 1993), so they should be assessed as part of an ergonomics evaluation (e.g. Grandjean and Kroemer, 1997). Related to this, from a literature review regarding tactile feedback, Barros et al. (2014) stated that haptic gloves can be used for ergonomic evaluation permitting the evaluation of force, manual strength, position and movement of the hands. Furthermore, adding force feedback to VR can enable the users to assess complex tasks such as assembly/disassembly (Gomes de Sá and Zachmann, 1999). Force feedback would also add natural and expected collision feedback, fundamental for the enhancement of realism. Gomes de Sá and Zachmann (1999) reported that after an interaction with a virtual assembly system, some specialists found that without force feedback, some assembly tasks were almost impossible to do. Kim and Vance (2004) pointed out that VR can provide a more realistic environment than on desktop computers, but collision detection is fundamental to give a natural environment and to facilitate the interaction between user and the object. Indeed in VA an object to object and a body to object interaction is required. Finally, Cardin and Thalmann (2008) observed that humans are able to discriminate targets location using torso-based stimuli. However, applications of whole-body haptic feedback in near-distance manufacturing investigations are lacking (Père, Meyaender and Merienne, 2006), and are thus a possible avenue for future research.

Haptic feedback is also useful in design, as Evans (2005) observed that tactile clues are important in product development, since the design of a product is a multi-sensory process and the manipulative control is fundamental. Bordegoni et al. (2006) demonstrated that haptic feedback enabled the user to simulate the sense of touch in VR, to assess the disposition of tools such as knobs, buttons, and emulate operations such as the opening of a door. Swapp et al. (2006) demonstrated that accuracy and task performance in virtual environments were enhanced with co-located feedback (i.e haptic feedback). Given these academic justifications, it is clear that haptic feedback can offer benefits for VR in automotive applications including design and ergonomics investigations. Another important advantage of haptic feedback is that it has been seen to extend immersion and usability and therefore trust in the technology (Durlach et al., 2005, Salanitri et al., *In press*)

Sound. Regarding sound in VR, one of the main studies on presence revealed that sound is one of the fundamental factors enhancing immersion, because it is part of a multisensory experience (Slater and Wilbur, 1997). Increasing the sense of presence has enormous importance in the VR experience, since it gives the sensation that the object displayed in the virtual environment is real and that the actions taken with it are the same that would be made in real life (Dinh et al., 1999). Moreover, sound gives a more complete set of information to the users about the environment (Jayaram. et al., 2001). This is important in a driving context, where sound can enhance the fidelity of the simulation (Lee, et al., 1998).

Virtual contexts. Contexts have been seen to have a "profound effect" on the use of a product, including influencing factors such as lighting or relative physical location between product and user (Maguire, 2001). Other studies have observed that there is a well-defined relationship between posture (as defined by context) and the ergonomics suitability of a task (Tichauer, 1973; Armstrong et al., 1993; Bridger, 1995). Studies have shown that road scene, and in particular forwards vision, is one of main cues in setting up a driving position (Barkawi, 2013). Considering drivable virtual road scenes, several vehicle package attributes, such as exterior vision and manoeuvrability, must be assessed in a dynamic environment (Herriotts and Johnson, 2012).

Studying driver distraction. One of the suggestions given by the stakeholders was to use VR for distraction evaluation. Related to the section on *Virtual Contexts*, a drivable scene is essential for driver distraction work (e.g. Burnett et al., 2013). Dynamic, fixed-based simulators have been found to have good relative validity for lane keeping in driving tasks (Reed and Green, 1999). VR has been reported as a suitable tool for evaluating design alternatives (Lawson and Burnett, *In press*); it is often considered to give greater relative validity than absolute validity (Reuding and Meil, 2004; Naghiyev and Sharples, in press). Eye tracking (and lane deviation) are standard measures of driver distraction (e.g. Burnett et al. 2013), which could be possible in a CAVE. In this application eye tracking would permit the assessment of eye position and pupil diameter, which are strong indicators of attentional focus (Sodhi, et al., 2002).

Accurate hand tracking for ergonomics investigations. Leap Motion (LM) is a recent technology permitting hand recognition without the need to wear special gloves or trackers. Using LM for grip simulation, Zubrycki and Granosik (2014) found that it provides information about position and orientation of the fingertip and has special functions to track position and orientation of objects visible in the scene. Moreover LM gives additional information (e.g. speed, and direction) on some movements (e.g. swipe, rotate). The LM can overpass some disadvantages of the existing technologies for hand tracking, such as sensor gloves which need to be calibrated and have to be worn.

Moreover, the correct reproduction of body parts is one of the most important factors in VR, because it improves the realism of the environment and reduces cybersickness. Studies show that the body representation in VR can facilitate the first person experience of body transfer allowing the users to move, work and interact in the virtual environment as realistically as the real world (Slater et al., 2010).

Markless tracking systems. Stakeholders expressed difficulties in donning the body tracker suit, and reported that the participation of more than one participant in the ergonomics investigation was '*awkward'*. Lawson and Burnett (*In press*) report that the ergonomics principle of designing for 5th-95th with a range of different body type configurations (long body, short legs; short body long legs) mandates that a number of different people assess any given task/workstation. This process would be faster with a markless system than with a body tracker suit. Other justifications for the use of markless systems have been given by Poppe (2007) who stated that motion trackers using markers are obstructive and expensive. Even though markless body trackers are less accurate than those with markers, they are a cheap and easy solution when markers are not desirable or applicable (Kehl and Van Gool, 2006). Markless body trackers can provide a fully articulated skeleton that digitizes the user's body posture and directly quantifies their movements in real time without encumbering the user with tracking devices or markers (Lange, et al., 2011).

*Olfactory simulation. S*ome participants suggested the introduction of olfactory stimulation for several purposes (i.e. air quality evaluation, and marketing). Yamada et al., (2006) found that participants were able to identify the location of simulated odours using a simulated olfactory display. Matsukura et al. (2013) demonstrated reasonable success for odour source identification on a desktop-based system. Thus, it may be possible that the location of a particular odour-producing component can be identified in VR. Moreover, as stated before, VR should stimulate all senses to develop the sense of Presence, which is the main factor underlying the VR experience (Purschke, et al., 1998). In one of the most important reviews of the characteristics of VR it is stated that adding olfactory stimuli provokes redundancy of the senses, enhancing the user's sense of presence (Steuer, 1992).

Colour. In the literature, it is demonstrated that the perception of a virtual environment is strongly influenced by the colours and natural conditions (Kruijff, Swan II and Feiner, 2010). Studying the effect of background colour in Augmented Reality (AR), Gabbard et al. (2010) found that the colour scheme and variety of an environment can affect perception and concluded that contrast, saturation and other colour characteristics are fundamental for the usability of AR. In their theory on Presence, Slater and Wilbur (1997) included colour as an important characteristic of "vividness", which is a fundamental factor of immersion.

Networked VR. One of the main issues observed from the stakeholders' interviews was the time spent for users to travel to where the VR systems are situated. Networked VR can permit distributed design, allowing multidisciplinary teams and people in different sites to work together on the same model (Lehner and De Fanti, 1997; Kulkarni, et al., 2011; Li, et al. 2005). The system could also be implemented on a desktop 3D monitor such as zSpace. Indeed, desktop VR systems have been seen to provoke fewer cybersickness symptoms than immersive VR (Sharples, et al. 2008). Non-immersive or desktop VR applications are cheaper and less technically daunting than immersive or larger alternatives (Ausburn and Ausburn, 2004).

Fluid movement and flexible part simulation. Examples of fluid simulation techniques can be found in the literature, for example: Enright et al. (2002) for water simulations, and Losasso et al. (2004) for fluids and smoke. Fluid simulation could be implemented in automotive applications to study the ergonomics of filling fluid containers (e.g. water, oil) or emptying tanks during service or end-of-life disassembly. Regarding flexible part simulation, Xia et al. (2013) stated that the geometry and behaviour of flexible objects is different from rigid ones, due to the different movements and actions that can be undertaken during assembly (e.g. deformation, bending, twisting) Moreover the simulation of soft objects has influence on the overall quality of the assembly (Xia et al., 2013).

Marketing. Marketing is a fundamental aspect of a product development. Lui et al. (2007) stated that with the possibility to simulate similar experiences as customers have in real stores, virtual worlds are able to enhance product knowledge, and analyse the attitudes and purchase intentions of customers. Research has shown that virtual reality is capable of positively influencing product knowledge, brand attitude, and purchase intention of consumers (Li, Daugherty, and Biocca, 2002; Suh and Lee, 2005).

Recommendations

Given the issues reported by the stakeholders, the identified opportunities, and the academic justifications described in the previous sections, a set of recommendations has been developed. These are listed below.

Address issues of depth perception in VR: through the use of rich environment, textured background, shadows, a multisensory environment and vivid/good quality colours.

Provide haptic feedback for more robust ergonomics investigations, including: i) the implementation of a haptic arm with force feedback for complex gross-motor tasks, which should simulate vibration, torque and force required to lift weight, and ii) the implementation of a system offering haptic indication of reach.

Implement collision detection: (human to object and object *i.e. tool* to object) for greater validity of manufacturing assessments and to overpass the limitations of desktop CAD modelling.

Improve multi-sensory feedback: including the introduction of 3D sound for manufacturing and switchgear assessments and olfactory simulation for air quality and market investigations. In addition to task-specific benefits, this is likely to increase *presence* in the virtual environment.

Use a markless body tracker system to enable representation of a range of body types in ergonomics investigations and to avoid the difficulties associated with donning a marker-based tracking system. This should include high accuracy hand tracking, for ergonomics assessment and for digital reproduction of the hands.

Provide virtual contexts, including a driveable road scene: the CAVE should be developed to allow components to be evaluated in realistic vehicle and driving environment (virtual) contexts. Driver distraction capabilities should also be provided through a driveable road scene and eye-tracking technologies.

Provide fluid/flexible part simulations: for higher fidelity assessments of manufacturing and service tasks.

Use VR for market research: to reduce the costs and difficulties associated with transporting physical properties to various markets.

Implementation a networked 3D technology: with desktop 3D visualisation to cut down on engineers' travel times between sites and address access issues to high-end VR technologies.

Discussion and conclusion

To remain competitive, industry has to be constantly up-to-date with the newest technological opportunities and must be willing to change existing systems and procedures to implement new and more efficient and effective ones. Indeed market requirements often demand continually increasing product quality, in less time, as exemplified within the automotive industry. As described in the introduction, the reduction of costs and the enhancement of hardware and software quality have led VR to being widely used in the automotive industry. Indeed, studies have shown that using VR in several and different processes of product development (such as design, assembly, prototyping) can increase the quality of the final outcomes, reduce the costs of the entire process, shorten time to market and improve the efficacy and well-being of users. In this context, analyzing the issues with virtual and physical properties and processes, and identifying new opportunities for VR, is essential such that industries can remain competitive and benefits from the latest research findings.

This review analyzed existing VR technology in a world-leading OEM, based on the experiences and requirements of engineers and users. This focused a literature review of possible improvements based on scientific advances in the academic literature. To the best of the authors' knowledge, it is the first of such a review at the intersection of VR use in the automotive industry and academic research. The importance of this work can be given with consideration of the bilateral perspectives of industry and research; while research is dealing with advanced concepts in the human use of technologies, it is essential to reflect upon their implementation and use in industry.

Concerning the outcomes of the review, many of the issues reported related to topics being addressed in the academic literature. Considering for example perceptual differences between real and virtual properties, the issue of inaccurate egocentric depth perception in Virtual Reality is widely recognized in the literature (for a review, see Renner et al., 2013). Regarding stakeholders' issues of lack of tool weight or collision feedback in ergonomics investigations, multi-sensory feedback, combining vision and haptics, is expected to offer performance benefits in tasks in virtual reality (e.g. Swapp et al. 2006; Gallace et al., 2007). Multi-sensory feedback is considered essential for some manufacturing tasks (Gomes de Sá and Zachmann., 1999), and is an important aspect of design (Bordegoni et al., 2006). Simulating additional senses (e.g. olfactory) is receiving attention in academic research (e.g. Matsukura et al., 2013) and offers not only task specific opportunities in automotive applications (i.e. identifying a foul smelling component) but can increase the sense of presence (Steuer, 1992). Advances in markerless body tracking reported in the academic literature (e.g. Poppe, 2007; Zubrycki and Granosik, 2014) would address the reported issues with marker-based tracking. The possibility for networked VR to address the stakeholders' issues with travel time and access has also been addressed in the literature (e.g. Li et al., 2004). These examples illustrate the finding that several opportunities exist for the development of VR technologies in the automotive industry based on academic research.

A limitation of this study is that only stakeholders who are existing users of VR systems were recruited to participate in the study. There may be other engineers or disciplines who could benefit from VR, but who are not aware of its capabilities or how to access it. However, the primary aim of the interviews was to guide the direction of the literature review. As many recommendations are applicable across engineering disciplines, it is likely that these changes would benefit new users of the VR technologies. Moreover, recruiting a representative from every engineering discipline would have been outside the scope of this research.

To conclude, this review aimed to identify new opportunities in the use of VR within an automotive manufacturer. It combined the opinions of stakeholders, who use VR on a daily basis, with a review of the most important literature on VR research. This work demonstrated not only that VR could improve several aspects of the product development process, but also suggests that constant reviews of existing systems and frequent studies of new opportunities from the academic literature will lead to greater competiveness by improving product quality and reducing time to market.

Acknowledgements

The authors would like to acknowledge Jaguar Land Rover for funding the research work on which this paper is based.

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