System based on abstract prototyping and motion capture to support car interior design

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1. Introduction

Comfort, ergonomics, habitability are aspects that car interior designers have to take into account during the development of new cockpits. Even though consolidated rules lead the design in this sense, they do not suggest in any way how making significant changes to car interiors according to the users' needs. Human perception of the internal space of a car relies on several psychological as well as physical factors [20] and their assessment is often very difficult to carry out.

Preliminarily, car manufacturer designers are used to perform studies by using virtual humans [5] software in order to assess the ergonomics and the space required by the car occupants. These studies allow them to get important information for the development of the cockpit. However, this information relates to common occupant postures and cannot predict non-standard habits of driver and passengers. [4] highlighted, in fact, that existing posture and motion prediction models must be based on real motion data to assure validity for complex dynamic task simulations.

Evaluation test conducted with real humans can be useful for this scope and generally are performed at the end of the design process, since it implies making a cockpit prototype with which the users have to interact. Consequently, also the results of these tests cannot help designers during the early stages of design process.

Virtual Reality technologies can help designer to anticipate the execution of these evaluation tests, since they allow for simulating the cockpit before making the first physical prototype. In particular, the possibility of simulating a cockpit partially real and partially virtual has been demonstrated to be effective in several studies [2][14][17]. However, the results of these tests still not provide the designers with useful suggestions in the very early stage of the design, since the virtual simulation relates to a cockpit that is already substantially designed.

The research, which is described in this paper, aims at addressing this purpose and presents a system that can support the generation of new car cockpit. The research focused on the issues related to the cockpit passenger's area that could gain many benefits from this system. In fact, cockpit passenger's area is usually designed as the symmetrical counterpart of the driver's area even though passengers have highly different needs in terms of comfort, safety and freedom of movements, if compared to the drivers.

The main objective of this research is the development of a system able to record passenger's habits during the execution of specific actions within the car. The system has been developed by integrating Abstract Prototyping technique with Motion Capture technology. In addition, a systematic procedure to elaborate and to synthesize the collected data has been implemented with the aim of making these data directly available as a generative input for the concept design process. The paper describes also a testing session conducted with subjects to evaluate the developed system. Subsequently, the outcomes

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of the testing sessions have been discussed, highlighting benefits and limitations. In the final remarks, some considerations about the future research possibilities in other application fields are presented.

2. Background

The first aim of this study is to observe car passengers' habits and making these observations useful for designers during the generation of new cockpits. The obvious question is: how recording, elaborating and synthesizing passengers' habits? Assessing passengers' habits in general is not simple, since human's behavior is deeply influenced by several subjective factors. Common investigation approaches are based on qualitative study of humans' habits. A qualitative approach, such as the analysis and the interpretation of the human movements recorded in a video, can provide insights to generate new concept ideas. However, the richness of information that can be gathered by video recording users' experiences is limited in the viewpoints and possibilities of analysis. The extracted insights are also influenced by the subjectivity of the interpretation and cannot be converted into objective data useful for modeling a cockpit.

Conversely, a quantitative approach would allow for collecting objective data that can be also statistically validated. Physiological signals, brain activity and human body movements are the most important objective data that can be collected. The study of human body movements, in particular, is the aspect of the human's habits that better fits with the purpose of this research. As discussed in the introduction, in fact, space required by the occupants is a constraint that designers have to take into account during the development of a cockpit.

The quantitative approach, hence, implies collecting data about the human body postures, which a subject assumes during the execution of actions within a real cockpit. However, in the early stages of the development process the new design of the cockpit not yet formalized. Therefore, in order to run user studies, a common approach involves the creation of rough prototypes that simulate the context of user experience. Although using an already existing cockpit for this purpose is certainly a possibility, a low fidelity setup seems to have a greater value in the moments of understanding and exploring the design problem. As other studies demonstrated [3], this approach enables users to focus on the design question, rather than on the artefact itself, they are interacting with. For this reason, the research proposes to make use of the Abstract Prototyping technique [13] to physically simulate the structure of the cockpit. The prototype should represent the artefact in a synthetic way, while avoiding realistic details. In this way, the participants to the test will be encouraged to undertake a creative and participatory attitude [1]. Similar studies were conducted in various applications such as: simple artefacts as game controllers, the simulation of an airplane interior, the health care environment [18], the investigation on a phenomenological level the user interaction with interactive products [6].

To record in real time the postures of subjects, instead, a Motion Capture system is needed. Current technologies propose many systems with different features and performance levels. For the purpose of the research, Optical Motion Capture systems are the best choice, since they guarantee a very accurate and precise tracking. Although Optical Motion Capture systems are widely used in several application fields [19] no extensive method addressing the use of human movements for design purposes was found in literature. One of the reasons for this lack of use could be the computational form of the data produced by an Optical Motion Capture system. The information results largely inaccessible for designers, who need a flexible and meaningful representation in a modeling environment. For instance, to effectively support the design process, motion data can be elaborated to suit 3D modeling software tools.

3. System for the acquisition of human movements

The system for the acquisition of human movements was developed with the aim to analyse the area of the cockpit that surrounds the passenger's seat. As discussed in the introduction, this area of the cockpit could gain many benefits from this analysis, because passenger can freely move within the cockpit and can assume postures different from the standard ones, which are usually used to assess safety and ergonomics. The system was implemented by integrating different elements according the considerations discussed in the previous section. In particular, the elements, which constitute the system, are:

- The cockpit prototype;
- Optical Motion Capture system;
- Rigid Bodies.

The cockpit prototype was implemented by following the principles of the Abstract Prototyping techniques (see Fig. 1). The prototype, reproduces the rough geometry of the cockpit passenger's area. It was implemented by using low-cost materials and the structure was designed in order to avoid interference with the Optical Motion Capture system. The base of the structure was built with plywood, the elements with more complex geometry were obtained by scraping high density extruded polystyrene foam (XPS) blocks and the surrounding structure were built with standard plastic tubular elements. To make realistic the passenger's seat a real car seat was located within the cockpit prototype. The dimensions of the cockpit prototype relates to a car of the C-segment [9], which can be considered the most common car type.

Figure 1. The Abstract Prototype of the cockpit passenger's area.

The Optical Motion Capture system used to capture the users' movements was composed by 6 Flex-3 cameras by OptiTrack© [16]. The 6 cameras were placed around the abstract prototype of the cockpit. The placement of the cameras was studied in order to reduce at minimum the occlusions during the acquisition. Optical Motion Capture systems are based on the elaboration of video streams coming from cameras to calculate the position of reflective spherical markers in the three-dimensional space. Usually, motion capture of human body implies the subject has to wear a special garment where several markers are fixed. This solution allows a very accurate tracking of the whole human body but is not practical for the purpose of this research. The research, in fact, aims at evaluating several subjects with different physical characteristics and consequently the garment should be adapted to each subject, in order to guarantee a good acquisition. In addition, total-body tracking needs of an initial calibration for each subject increasing the time and the complexity of every single session. Consequently, it was chosen to track the parts of the human body that can provide the most useful information for the aims of the research. These eight parts are: head, chest, arms, knees and feet. Each part was tracked by using the Rigid Body modality.

A Rigid Body is a wearable object identified as a cluster of reflective spherical markers rigidly arranged in a univocal configuration. Eight different Rigid Bodies were implemented by using thermoformable plastics, in order to adapt them to the anatomy of the human body, and small belts with Velcro©, which allow the subject to easily wear them. The Optical Motion Capture system is able to track position and orientation of all Rigid Bodies at the same time by recognizing frame by frame the different markers configurations. Fig. 2 shows the Rigid Bodies developed for the eight parts of the human body.

4. Testing session

The idea behind the proposed research is to provide the designer with a system to quantitatively capture passengers' habits and consequently nurture the concept of a new passenger's cockpit area that best fulfil their needs. To identify the most characterizing habits of car passengers, a preliminary study in field-research modality has been conducted by designers and it has dealt with the observation of users in a real context.

This preliminary observation was aimed at identifying the actions [8], corresponding to users' needs, to be further explored in the testing sessions. The observation was carried out with 9 participants, 5 male and 4 female, video-recording them with a frontal GoPro© [11] camera and one hand-camera in the back seats. Participants were brought on a medium-length journey (average 40 minutes), after which they were interviewed about the level of comfort, their needs and their expectations. Through these first results, four actions were identified: (1) the assessment of comfort in posture; (2) the interaction with either people or objects in the back seats; (3) the

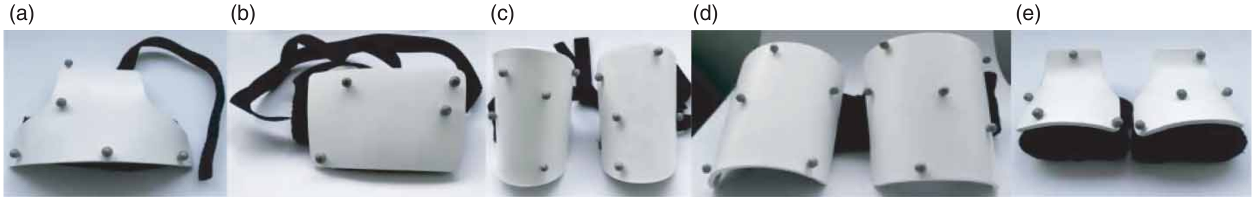

Figure 2. The Rigid Bodies developed for the eight parts of the human body: (a) head, (b) chest, (c) arms, (d) knees, (e) feet.

placement of personal items, such as bags, coats, etc.; (4) the interaction with smart devices.

Subsequently, the system described in the previous section was used to organize the testing session in the lab. The objective of the test was tracking the passengers' movements while simulating and recalling their personal experiences as passenger beside the driver and executing the actions identified in the preliminary study. The testing session has also been useful for evaluating the eff ectiveness of the proposed system. The expected output was a set of data that constitute a volumetric 3D model representing the (desired) space of interaction for passengers. The data acquired during the tests has been subsequently elaborated to make them meaningful for designers, and representable in a 3D modeling environment.

Also for this testing session, 9 participants (5 male, 4 female, aged 25–52) have been involved. The testing session was split into two phases: during the first phase, participants were asked to recall one meaningful experience as a passenger in the car. This phase was based on the Open Interview technique, according to which people can reveal important issues and opportunities by narrating stories about their daily experiences.

The second phase, instead, was conducted by using a semi-structured approach [7], by following a set of predetermined questions to tackle the four actions causing problems as defined i n t he p reliminary t est. Accordingly, the interviewer is allowed to follow new ideas and paths of research that may be brought up during the session. The interviews were video-recorded not only to document participants' feedbacks but also to provide a reference for the subsequent steps of motion data analysis. During the tests, the users' movements and gestures inside the Abstract Prototype were captured and stored. Fig. 3 shows a user during the execution of the test.

4.1. *Elaboration of data*

The testing session generates a big amount of data and a specific post-processing procedure was needed in order to make them suitable for the subsequent synthesis. In fact, this kind of data is diffi cult to manage as it is and it has to be converted into a synthetic representation within 3D modeling software.

The first step, after completing the testing sessions with subjects, was to elaborate the data in order to discard any error that occurred during the session. Indeed, the system calibration and the design of the wearable markersets may heavily influence the delicate phase of motion capturing. Yet, occlusions caused by some movement, parts to be trimmed, misidentification of markers and other accidents can take place. These accidents generate gaps in the trajectories accomplished by the Rigid Bodies. The elaboration of the data includes three different actions:

1) marker relabeling (for gaps $>$ 200 frames);
2) gap filling (for gaps $\leq$ 200 frames);
3) track smoothing (filter cut-off frequency $=$ 1 Hz).

Marker relabeling is an elaboration that manually allows identifying markers constituting the Rigid Body. This error occurs when the Motion Capture software [15] is not able to automatically associate the captured markers to the Rigid Bodies, which should be recognized. This action was applied when the length of the gaps exceeds 200 frames. For the other trajectory gaps ($\leq$ 200 frame), instead, the automatic gap filling was used. Gap filling allows interpolating the gap with a polynomial function. The degree chosen for the polynomial function was three. Finally, to reduce the noise of the acquired data the track smooth function was used and the filter cut-off frequency was set to 1 Hz. At the end of this first elaboration step, all the trajectories of Rigid Bodies are completely defined.

The second elaboration step was extracting the points constituting the Rigid Bodies trajectories, and to make them suitable for 3D modeling software. During the extraction, the Motion Capture allows choosing the number of frames to export for each second. This choice deeply influences the final graphical elaboration in a 3D modeling software. After a series of trials, the best choice was 16 frames per second. The exported data were collected and stored in a comma-separated values (csv) file. Unfortunately, the organization of the data within the file does not allow importing the point cloud directly into a 3D modeling software. In addition, this file contains

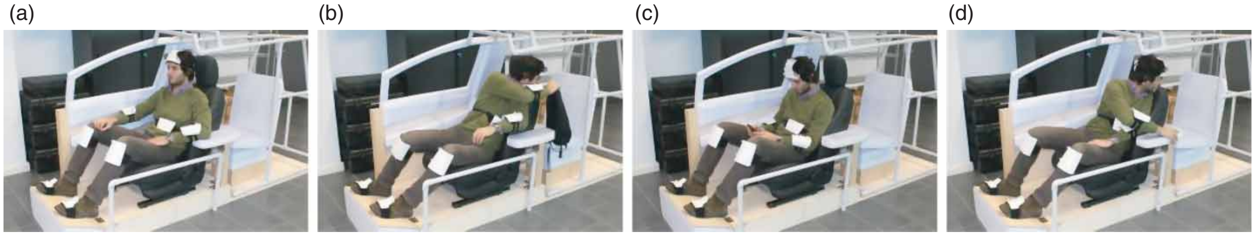

Figure 3. User during the execution of the four actions in the testing session: (a) researching of maximal comfort, (b) positioning of personal objects, (c) using of smart devices, (d) interacting with the back seats.

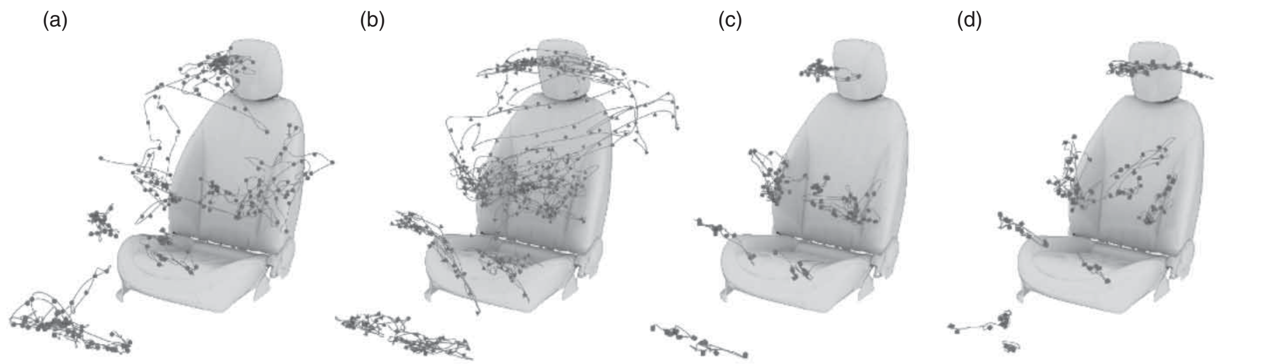

Figure 4. Results of the motion tracking data representing the four actions after the elaboration: (a) interacting with the back seats, (b) positioning of personal objects, (c) researching of maximal comfort, (d) using of smart devices.

information about all Rigid Bodies and it is not possible to select the point cloud of a single Rigid Body trajectory. For this reason, a software application was implemented to recognize and export from the csv file information associated with a single Rigid Body. The software application generates a new file, one for each Rigid Body, listing the (X, Y, Z) position of their centroid for each frame. At the end of the second elaboration step, the so-defined files can be imported and re-elaborated into the 3D modeling software.

The 3D modeling software used to re-elaborate the data was a 3D commercial modeling software based on NURBS mathematical model. Once the files were imported into the software, numeric data are represented as Point Clouds, which represent the first step towards a sensible visualization of data. Yet, Point Clouds have still limited possibilities in terms of characterization and modifications possible: for example, it is not possible to differentiate participant, actions and the specific Rigid Body associated to each area of the human body.

To generate curves, which effectively represent the Rigid Bodies trajectories, various curve-generation methods were tested. Spline interpolation was considered as not effective, since errors due to the precision of the Motion Capture system make the curve irregular. Consequently, the visualization and the interpretation of the generated spline result to be difficult. Bézier curve, instead, reduces the effect of the precision errors and the curve appears smoother. In particular, a Bézier curve with degree = 11 has been used. However, the curves may still appear redundant in some part of the trajectory. To reduce the number of the redundant curves, the control points of the curve were deceased up to 10% of the original ones. At this point, all the trajectories corresponding to users' movements and interactions can be generated in the same way.

In order to visualize them in a more significant manner, the assignment of a graphical representation reference to each variable is needed. This can be highly correlated to designers' subjectivity; as an example, trajectories can be represented by small pipes, to each participant can be attributed a specific colour, and symbols can highlight the differentiation between themes. In other cases, the distinction between each Rigid Body can be more meaningful than the one on a single participant, and colours can be distributed according to this criterion. Anyhow, at the end of this phase, designers will achieve a structured visualization of human movements that depicts the user-product interaction in a 3D modeling software. Thus, they are able to exploit these data as the starting point of the design process, to start shaping the concept design.

Fig. 4 shows the results of the curves generated from the Point Clouds captured during the execution of the four actions identified during the test.

4.2. *Possible uses of the motion data*

After the elaboration, the data have been used to carry out some analysis of the space occupied by the subject in the cockpit during the execution of the actions. To perform these analyses a 3D model of a cockpit of a generic C-segment car was imported into the 3D modeling software. To align the acquired data to the 3D model of the cockpit some significant points of the seat have been used as reference points. After these settings, the user of the 3D modeling software has the possibility to show and hide all the motion data acquired during the testing session. To make this operation easier, the data were clustered on different layers with different colours. Each layer relates to the data of the movements of the four actions for a single subject. In this way, the user can visualize the data in different combinations choosing between type of the action and subject (e.g. all actions of a single subject, a single action of all subjects, etc.). In Fig. 5, for example,

Figure 5. Visualization of the motion data relating the four actions of a single subject.

the motion data related to the four actions of a single subject are shown in different colours.

The visualization of the data within the 3D modeling software allowed further identifying some areas never crossed by the subjects. These areas can be filled by using the freeform geometries provided by the modeling software. As shown in Fig. 6a, a yellow freeform geometry has been created to highlight the not-crossed area on the lateral side. This freeform geometry, for instance, could be subsequently used as a geometric reference to create a lateral support for the passenger. In addition, the measuring tools of the 3D modeling software could be used to take some specific measurements of the acquired movement data in an easy way, as shown in Fig 6b.

The possible uses of the motion data above proposed have to be considered an attempt to show the potentialities that the implemented system and the motion-tracking data can provide. Obviously, car interior designers can find several other manners to exploit these data visualizations in a way that reflects not only their personal design attitude, but also their subjective interpretation of the motion data.

Compared to results obtained by video-recorded user's observation, human motion data visualizations bring a number of benefits and limitations. As highlighted in Table 1, 3D modeling software tools allow exploring human movements by multiple perspectives, instead of from the fixed viewpoint of a recording camera. Moreover, in the modeling environment, users' actions and correlated movements can be measured and quantified, by extracting secondary pieces of information as angles, areas, distances, etc., as shown in Fig. 6a-6b. Static images, as pictures or snapshots from videos, cannot be overlaid in any way. Conversely, the method here presented allows us to analyse the overall volume of users' gestures as a whole. By presenting motion data in their 3D nature, user information can be used as the starting point to actually model the product. Many other possibilities unfold beyond: user anthropometrics can be imported and compared within a modeling environment, while they are incompatible with two-dimensional images. However, the method presents some intrinsic limitations. First, Motion Capture is usually considered an expensive technique, both in terms of time and resources. One of the research goals was in fact to guide designers and provide enough structure to carry out a similar research in a reasonable time frame, and reduce setup and processing effort. Secondly, depending on the specific design problem, users' movements may be of minor relevance for the design process, or the lab environment could bias the tests' results. Lastly, the aim of this work is to prove the

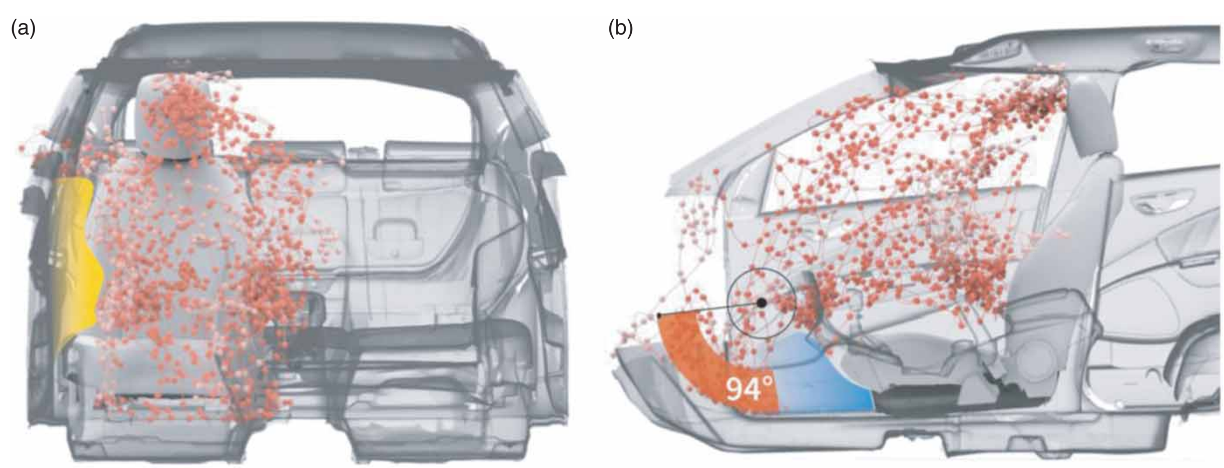

Figure 6. Visualization of the motion data relating two actions of a single subject: (a) inclusion of a freeform geometry, (b) specific measurement of the acquired movement data.

Table 1. Comparison of video observation and motion tracking techniques.

	Video Observation	Motion Capture
Environment	field	in-lab
Information on	quality of movement	shape of movement
Perspective	single	multiple
Nature of data	2D	3D
Interpretation of results	subjective	objective
Visualization of data	partial	single + overall
Output	non-measurable (snapshots, etc)	measurable (3D model, visualizations)
(Can have) Influence on concept	indirect	direct
Integration of user anthropometrics	no	yes

benefit of having complementary results from standard observation techniques and motion tracking, rather than assessing the superiority of one of them.

5. Discussion

The visualizations of motion data proposed in this research give information on the trajectories of the human movements and the areas where users interact the most. This will give the possibility of shaping new concept of the passenger side of the cockpit as a negative model, i.e. using the data as a starting point for the concept generation process.

The concept design could be based on solid, reliable data (motion tracking data), merging effectiveness and style. Through this system, motion-tracking data could be also coupled with interview results. These provided other interesting insights, outlining some critical issues for every action. The main asset found was the need of an area specifically designed to better integrate the passenger's needs. This involves breaking the symmetry in the car interior design, thus guaranteeing a larger flexibility in the movements for passengers.

The tests highlighted the participants' willingness to interact with the back seats, especially in presence of children, pets and, in general, for long journeys. They showed also to be uncomfortable in their postures, especially with their legs and arms. They claimed to perceive the need of a flexible lumbar support and more space for legs, as well as they would appreciate to have armrests.

However, the study presents some limitations and some improvements have to be implemented. Firstly, the criteria selected to display motion data are now restricted to the position and frequency only. Yet, a semiotic approach to human movement as the one discussed by [12] could expand the possibilities, although it would increase the complexity of the data visualization. Moreover, the creation of pipes was considered as the most appropriate way to render the motion trajectories and the information on the position of each Rigid Body.

Other possible approaches involve the creation of gesture areas, i.e. polygonal meshes generated over the Point Clouds. This process could better highlight the volume of interaction, while neglecting the information on the trajectories and orientation. The integration of 3D human models, as retrieved in [10], offers another possibility of investigation. Nevertheless, the most promising prospect is given by parametric modeling software. In this way, it will be possible to display and organize a larger number of parameters, such as the speed, the orientation, etc.

6. Conclusions

This paper presents a system to capture and synthesize car passenger's habits during the execution of actions, which were defined in a preliminary study conducted in real environment. The authors identified that motion-tracking data can be a useful way to supply meaningful insights to designers during the concept generation process. The testing session performed with 9 subjects have demonstrated that human movements can be used to infer the users' personal experiences of a space. The captured motion tracking data can be used to generate 3D geometries to shape new concepts of the passenger side of the cockpit. A systematic procedure has been implemented to allow the treatment of the collected data to obtain a graphical representation, which can be easily used within standard NURBS-based modeling software. The visualization of this data within the modeling software allowed identifying and analysing the areas, which were not involved by the movements of the subjects. By presenting capture results as a three-dimensional representation, designers can actively interact with the model, while standard observation techniques only allow a passive fruition. From these analyses, designers could take inspiration to generate a new the cockpit concept according the non-standard movements executed by the car passenger.

However, while the synthesis of motion tracking data has been sufficiently addressed by this study, the designers' viewpoint should be further investigated, to understand how they could exploit this kind of data for modeling new shapes. The authors identified three possible ways of how designers can make use of motion data: a) by navigating through the several visualizations and interpreting them; b) by using the volume of interactions as a modeling reference to shape the concept of the new product; c) by taking specific and punctual measurement of distances, areas, angles, etc. The authors make the hypothesis that the effectiveness of the system could be validated through other case studies, with other kinds of products. All the products involving a spatial interaction seem to be suitable for the aim; as for those, the study of human gestures acquires more value. In this respect, a correlation between the semantics of gestures and movements can give new possibilities of interpretation. Finally, further evaluation tests would be beneficial to clearly assess the costs in terms of time and resources that the use of this system implies.

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