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Multi-user interface for co-located real-time work with digital mock-up: a way to foster collaboration?

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Abstract Nowadays more and more industrial design activities adopt the strategy of Concurrent Engineering (CE), which changes the way to carry out all the activities along the product's lifecycle from sequential to parallel. Various experts of different activities produce technical data using domain-specific software. To augment the interoperability among the technical data, a Digital Mock-Up (DMU), or a Building Information Model (BIM) in architectural engineering can be used. Through an appropriate Computer–Human Interface (CHI), each expert has his/her own point-of-view (POV) of a specific representation of DMU's technical data according to an involved domain. When multiple experts work collaboratively in the same place and at the same time, the number of CHIs is also multiplied by the number of experts. Instead of multiple CHIs, therefore, a unique CHI should be developed to support the multiview and multi-interaction collaborative works. Our contributions in this paper are (a) a concept of a CHI system with multi-view and multi-interaction of DMU for multiple users in collaborative design; (b) a state of the art of multi-view and multi-interaction metaphors; (c) an experiment to evaluate a collaborative application using multi-view CHI. The exper-

imental results indicate that, in multi-view CHI working condition, users are more efficient than in the other two working conditions (multiple CHIs and split view CHI). Moreover, in multi-view CHI working condition, the user, who is helping the other, takes less mutual awareness of where the other collaborator works than the other two working conditions.

Keywords Computer–human interface · Collaborative design · Multi-view · Computer-Aided Design

1 Introduction

Concurrent Engineering has changed the style of PLM from traditional sequential engineering to a parallel mode in order to reduce the overall product development time [1]. Experts from different fields now can work collaboratively at the same time. Their domain-specific software exchange technical data under a unique digital mock-up. Thus, PLM software packages need Product Data Management (PDM) systems, as well as synchronous or asynchronous, local or remote collaboration tools and if necessary, a digital infrastructure allowing exchanges between software programs [2]. Meanwhile, an expert can interact with DMU in both visualization and manipulation through one CHI. Because of the characteristic of multi-representation of DMU, multiple users should interact with DMU through multiple CHIs. However, in co-located real time collaborative working conditions, multiple users nowadays still have to communicate through their own CHIs. This motivated us that one single CHI system to support multiple experts can help the co-located real time collaborative works.

In this paper, firstly, we discuss the industrial background of supporting multiple users with CHI system. A summary of multi-view and multi-interaction devices have been made

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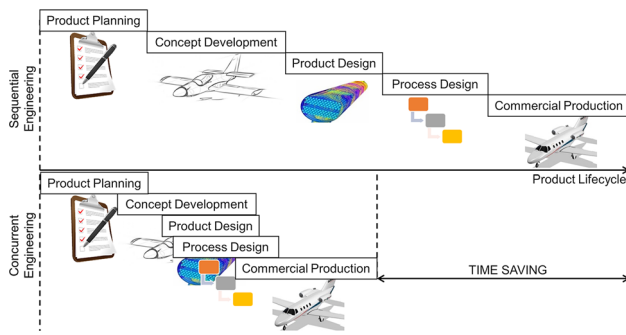


Fig. 1 *Up* traditional sequential engineering; *down* concurrent engineering

in Sect. 2. Secondly, we propose a solution of supporting multi-user using single CHI in Sect. 3. Finally in Sect. 4, we design an experiment to prove the multiple users' efficiency using multi-view CHI comparing to multiple CHIs or mono CHI with subdivided views.

2 Multi-user collaborative interface

2.1 Concurrent engineering

Concurrent Engineering is now a common reference in industry. Concurrent Engineering has changed the way to design an industrial product, from sequential engineering to a parallel mode in order to reduce the overall development time [1, 3]. As shown in Fig. 1, the industrial design activities contain product planning, concept development, product design, process design and commercial production. The strategy of Concurrent Engineering changes the way to carry out all the activities in a parallel way instead of traditional sequential step-by-step style. It is an integrated product development process strategy with which everyone involved may work collaboratively in a certain interval. Different product lifecycle activities may have some overlaps at the same time [4], especially when the product needs a design review by a group of experts from different domains.

Within these overlapped activities, experts join in a collaborative working environment. This pattern of collaboration in design is supported by a design method of interactive product design. The interactive product design is a constructive approach in which user-integration is highly considered during the product design process [5]. It is of major economic and strategic importance in the development of new and innovative industrial products [2]. Based on the strategy of interactive product design, the creation of a product is considered to be evaluated by end-user satisfaction of the realized interface [5]. The usability [6] of the user interface, which is a key aspect for the success of industrial product design activities, will be described and tested in the stage of

early design. The design of the end-user's Computer–Human Interface of a product for interactive product design activities will be discussed in Sect. 2.4.

The interactive product design in Concurrent Engineering affects the way how experts interact with machines and how experts interact collaboratively with each other. It embodies the needs of collaboration among experts from several domains. The evaluation of usability of interactive product design shows the effect of collaboration in design.

The content of interactive product design in industry can be Digital Mock-Up, which will be discussed in the next section.

2.2 DMU and its representations

A DMU is built up by a large package of data itself, together with the product structure and attributes of this package of data [1]. This package of data just comes from all the product lifecycle activities where DMU is integrated into.

Every product lifecycle activity, in the context of Concurrent Engineering, needs expert and dedicated tools. These tools mainly contain Computer Aided Design (CAD) tools in the product development process of design, Computer Aided Engineering (CAE) tools in -analysis and Computer Aided Manufacturing (CAM) tools in manufacturing, also other softwares from different domains. Various experts use domain-specific software to produce various data [7]. These experts then can share information with others by sending the data of the special software into a global database [8]. Similarly, in architectural engineering, a BIM model is a set of interacting policies, processes and technologies containing building design and project data in digital format throughout the building's life cycle [9]. For both DMU and BIM, the technical data from all the activities during entire product lifecycle are restored in this unique data package. Normally standard commercial DMU and BIM tools are widely used: CATIA®, Autodesk Inventor LT™, AutoCAD®, Autodesk Revit®, Civil 3D®, Microstation®, Novapoint Virtual Map™, etc. These tools act as a set of data package for their different end-users.

On the other hand, DMU can offer data to every product lifecycle activity of CE according to the special needs of the expert and tools.

It is one characteristic of DMU that it has multiple representations of technical data in different forms [10, 11]. E.g. an aircraft sketch, a part or an assembly, a mesh model for analyzing, a point cloud for reverse engineering, these are all representations of DMU. Since a DMU has multi-representations so that multiple experts can put in and take out information from one single DMU.

Here we can give DMU representation a further explanation concerning experts' POVs. Each expert considers the contribution to the product through one POV of the whole

product development according to his/her special skill. POV of DMU has two levels of meaning.

In the first level, POV is a professional perspective from which DMU is viewed. If two experts have different POVs of this DMU concerning different professional domains, the needs of their data form may basically be different. Obviously their representations received from DMU are not same. E.g. a sketch model and a mesh model are totally different. If the POVs are same, that is to say the professional perspectives of these two experts are same so that the representation for them actually is same one.

In the second level, POV is the spatial property (i.e. position and orientation) of the point from which DMU is seen. If two experts are in different domains, the representations of DMU for them are different. The representations of DMU are not dependent from their POVs. They can look at a same place, having a same POV or they can look at different places, having different POVs. E.g. two experts may look at one DMU representation respectively in left direction and in right direction. Two experts generate two POVs but they work with only one representation. Another example is that two experts may look at the same spatial position so that they have the same POV. However, since their domains are different, they have two representations of DMU.

Thus, from the viewpoint of experts, the data to choose from DMU depends on their special perspective of DMU. Experts can benefit from the characteristics of DMU's multi-representation so that their multi-domain work can be achieved.

2.3 Collaboration and interoperability

Since experts need to work in parallel style with different DMU representations in the concept of Concurrent Engineering, they should search a way that they could work collaboratively to deal with the real industrial cases in product lifecycle.

During the product lifecycle, regular project reviews can strongly summarize the current work and assign the work of next stage by making modifications and proposing solutions to both strategies and technical details [1]. Known as a part of collaborative design [12], project review is often conducted by gathering experts in a same room, sharing information and making decisions. The content for project review normally relies on the information generated from DMU [13]. A DMU provides different information representations and each expert can choose the one from his/her POV. Simultaneously the experts exchange their opinions according to their specialties [14]. Then they could discuss and communicate in real time.

This typical co-located real time work condition needs collaboration among both the domain-specific software and the experts. The development of the collaboration tools to

support working during co-located real time project reviews is important.

The collaboration among experts would be realized only if they know their contributions and their constraints to the other collaborators. These could influence others on setting and managing the operational conditions of work in real time [15]. In order to reduce misunderstanding among experts and to save the collaborative working time, many works have been done to improve the interoperability among engineering software as well as the output model files [16]. E.g. Model-based approaches have been proposed that those models exported by several expert tools can be shared as collaboration knowledge in domains of mechanical design and eco-design [17,18]. Here interoperability is defined as the ability to work together for a common task and/or information exchange [19]. The supporting tools' interfaces are completely understood for working with other products or systems.

As described on the left of Fig. 2, four experts are working separately in four domains of aircraft. Each one of them could export one format of data file, which could be software-based or model-based files according to the four different domains. To collaborate more easily, the approach we present above has adopted only one data format from DMU, as shown on the right of Fig. 2. Each expert could work with one representation of DMU and export the same data file, so that the others could at least use this file technically. The interoperability among all the domain-specific softwares, which involves the interfaces among machines and tools, could be enhanced.

2.4 Computer-human interface

All the activities during collaborative works are conducted not only by software but by human-beings as well. Consid-

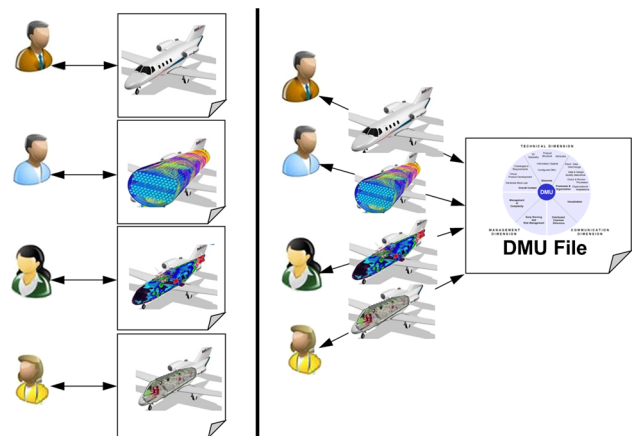


Fig. 2 *Left* users interact with different software and different data formats; *Right* software-based and model-based approaches allow users to interact with one DMU model with one file format

ering the interactive product design, the interfaces between human and machine or human and tools are also taken into consideration. Since interoperability among tools has been improved, the facilities in communication among experts are to be enhanced.

Computer–human interface (CHI) is described as medium for communication between the computer and the human user. Because of the development of computer science, the usability of a CHI is becoming more important when one CHI is compared with another CHI [6]. Besides having the basic feature of the CHI, what human factor reflects to this CHI is very important for evaluating this CHI.

CHI is usually a bridge between user and machine. Each user can have a certain CHI according to his preference. Being in a collaborative task, users may have different kinds of CHIs in use. These CHIs are still barriers among different users. If they want to discuss something they should first work with their special CHIs. To collaborate, the interoperability of CHIs from different representations is becoming more important.

Normally CHI mainly concerns both complex representation and multi-user interaction [20]. To build this kind of CHI, we should first consider the multiple POVs of this CHI. The synchronization of heterogeneous representations become a key point to organize collaborative activities [16]. Multi-view systems overcome the drawback of separated displays. When one's eyes switch between displays to collaborate corresponding information, separated displays will cause mental transformation in cognitive psychology and reducing an individual's performance [21].

The co-located synchronous project review CHI system usually adopts private view devices like laptops and tablet computer. Experts gather in a meeting room with their laptops in their own hands. An extra larger screen is usually available to show shared information among the experts; one can put the content of from his/her private view to the shared screen in order to diffuse the information to everyone. When one sees others' screen, he/she still cannot understand those domains because of the unfamiliar information on the screen. This occurs when the experts are from all other domains having different techniques, different educational levels and culture backgrounds, even having different languages [20]. They don't have the same knowledge in their mind and cannot exchange information in real time. This may increase the difficulty of discussing and negotiating with others.

When attending a project review, in which facial expressions and hand gestures interaction are important to express ideas to each other, experts require more face-to-face communication. A visualization system to represent experts multiple contents in a shared visual space is often applied. Normal displaying method for multiple contents is always using single laptop or large screen wall. Experts put several contents from different domains together on one screen. One content occu-

pies one fragment of the screen. If expert wants to compare information for two domains, he/she has to find the contents by moving eyes physically to deal with the displaying fragments. This may reduce the expert's concentration psychologically and increase the possibility of misunderstanding and the complexity of communication [21].

Interaction allows human and machine to communicate with each other. An intelligent CHI will allow users to interact with it using multiple metaphors and to interpret one metaphor to more than one single command [22]. Each expert could interact with the display system so that human machine interface could be realized and could be applied to collaborative team work. Different interaction metaphors [23] could be applied according to expert's special needs in order to conduct a navigation and manipulation of the object.

To gain multi-view and multi-interact effect for a CHI, many technologies has been used. In the next chapter, a state of the art of the technologies and devices that can create multi-view and multi-interact system, as well as the applications that are using these devices is presented. Benefiting from multi-view devices, the applications are then discussed whether they are good references for a DMU-like collaboration.

2.4.1 Multi-view devices

Many technologies for vision have been widely used to represent multi-views. With the development of CHI and virtual reality technology, the approach of multi-representation for DMU became diverse.

Nagano et al. [24,25] applied the polarized glasses based stereoscopy technology to multi-view approach. Two original glasses are restructured by putting two left eye lenses together and two right eye lenses together as two new pairs of glasses. Two users can get two 2D POVs.

Matusik et al. [26] redefined autostereoscopic screen-based devices to display 2D images from different POVs. Using similar technologies of generating 3D stereoscopic, parallax-barriers and lenticular sheets screens are transformed into many 2D POVs. Each user can see a 2D image in a right direction and a fixed angle.

Mistry [27] improved the shutter glasses technology for getting different POVs. Because 60Hz is the lowest frequency for human to form a continuous image and to avoid flickers, we can consider how many 60Hz POVs can be provided by the shutter devices. That is also the number of users that can be provided by this device. Two original 120Hz glasses can be made into two pairs. Each one gets a 2D POV in certain interval. A co-located multi-view collaborative visualization table is proposed in [28]. It uses a 120Hz screen with shutter glasses and polarized projector so that two users generate 4 POVs. C1x6 [29] is a combination of high frequency shutter glass system and polarized glasses. A co-located multi-view

system with 12 POVs is realized. Also, with a combination of shutter glasses and passive stereoscopic 3D system, a co-localized multi-user collaborative immersive CAVE-like display approach is proposed in [30,31].

There are also approaches which are not using 3D display technology. Kim et al. [32] uses an old fashion screen which displays clear image only when line of sight is perpendicular or tilted less than a certain angle to the screen. Taking advantage of this drawback, two POVs from each side of the screen and one POV from the exact perpendicular position can be realized. Dynallax [33] uses an active LCD with a dynamic barrier which can arrange barrier in four directions. With a 3D scene composed of four channels and tracking the users' positions, two views are present four POVs. Kakehi et al. [34,35] proposed a projected table top with separate projectors for each user. They use lumisty film, which is transparent only when user looking vertically in front of the material or within a certain angle ranges in on direction. With two lumisty film crossovers, 4 POVs in 4 directions are created. As we discussed above, for a multi-view co-located system, the importance is to create as many POVs as possible. For anaglyph and polarization approach, normally we obtain two POVs. For shutter glasses approach, the screen refresh rate defines how many separated views can be offered [26]. All of them have to face their shortcomings, such as color distortion for anaglyph images, less brightness for polarization, and flicker for shutter glasses. For screen-based stereoscopic system, developing multi-view support system means to create POVs for parallax. The disadvantage is the limitation of viewing range and stable viewing angle.

2.4.2 Multi-view applications

There are a lot of multi-view display applications. From a technical perspective, they do use different technologies to display different contents for multiple users. But from a collaborative perspective, whether the task in the application has to be accomplished by two or more users collaboratively still needs to be discussed.

If two users have no influence on the working content, multi-view support system will have no influence, even worse it brings negative effects. There will be no difference if they work separately. It seems that they work collaboratively only in order to save one device.

So now we describe the criteria of the effect that co-located multi-view support system brings collaboration to experts.

Interferential The system brings conflict between users. It is better to work separately. When multiple users have similar interactions with the displaying content, e.g. pointing at one position on a screen, they may have physical conflicts. The multi-view system has negative effect of conflicts.

Useless The system has no added-value. If there is no relationship among different contents, this multi-view system will have nothing different with multiple screens for each user. So it is unnecessary to use multi-view system if the different contents have no collaborative relationship.

Helpful All the systems except the interferential ones and useless ones are DMU-like collaborative. Different contents more or less have relationships inside them so that if one gets changed, the others would be updated in real time.

We use these criteria to discuss collaborative effects of multi-view applications with related works using multi-view devices.

One application [24,27] is that through multi-view devices, two users look at one sentence on a paper. The sentences have been translated into two languages. Each user can only understand what he sees in his special languages. These multi-view devices really helped the collaboration of understanding languages.

High frequency display like PlayStation® 3D Display with SimulView™ Technology and Samsung® OLED TV provided applications with which the two users play two games separately on a same screen. From the perspective of collaboration, multi-view system in this application is useless because if two users are provided two screens separately, the effect from device will not change. The same application is described in [34,35]. Two users can sing and dance separately by watching different content on a same screen. But the two activities have no collaboration. It is useless to display these two activities on a same screen.

The applications in [32] provided a multi-view screen that has three areas for three users. Two of them can play a face-to-face card game from two opposite sides of a screen. The third user is in charge of a game judging using a slice of the screen in the middle of the two former users. This screen with three separated POVs is helpful for playing this collaborative card game. The other card game application, described in [34,35], is for four users. This card game does not need everyone to point on the same screen, which is a collaboration situation in a typical card game. This card game can also be conducted separately, just as online card game. So this application is useless for collaboration.

One application of [28] is that two users manipulate pictures separately and choose pictures in a specific zone on the screen to make an album for themselves. Another application is that two users collaboratively annotate on a map to generate a path through communication. Two users are provided separately two maps of the same region but with different information. From the view of collaboration, these two applications are really helpful for collaboration between two users who have different constraints to their own part, like different themes of images or different traffic information on a road. However, due to the interaction of both users'

hands and the screen, the author can see the interference situation but not significant.

A co-located multi-view system with six 3D POVs, has been applied to see and to manipulate a 3D model for six users [29]. Another application is that two users work in the virtual assembly [31]. These two applications create enough POVs for multiple users, but the users are still dealing to a single representation of DMU. So there is nothing helpful with collaborative work.

As we discussed above, for real time co-located collaboration, multi-view support system enables different users to share a display device. More importantly, the application for this system has a strong requirement of information relationship in multiple contents. Unlike a lot of applications that can actually be done separately, a DMU-like application for co-located real time collaboration among multiple users needs more multi-view system.

2.4.3 Multi-interaction

To realize a multi-interaction CHI, many works have been done by extending the existing CHI from single interaction to multiple interactions.

Vogel and Balakrishnan [36] presents a CHI for four users differed from the distance away from a screen. They can control the displayed content by gestures. In addition the way of interaction used by one user is different from other users. This CHI can help four users interact with the content at the same time without any interference among the users. This is a good example for giving different interaction strategies to different users. However, if the users could choose their own way to interact, that will be much more ergonomic.

Sreng et al. [37] provides two users a CAVE based immersive system, especially with gesture-based manipulation device, speech recognition device and haptic input device to interact with virtual models in multimodal mode. For different objectives of manipulation, this system can provide users a mixed rendering and multimodal feedback, which is useful in complex virtual scenes such as virtual assembly. This is a good example of multi-interaction devices utilization in virtual reality immersive environment.

Song et al. [38–40] provides users special working medium such as a stick or a ring to interact with the virtual object. Meanwhile, special metaphors for interaction and a set of interaction principles are defined in a proper manner. This might be equivalent to the creation of new device and redefinition of the metaphor for the novel device. Users can feel free to define the metaphor with imaginations.

Bell et al. [41] lets users to choose methods to select an object. For example, a user may select an object if he/she holds their hand for more than a specific period, or if they make a rapid poking motion at the object. This approach

allows user to define the proper interaction metaphor according to the willing.

As we discussed, the multi-interaction of this CHI system to support multiple users should be designed not only in using different device, but also in allowing different interaction metaphors. Users are given enough freedom to define the interaction metaphor from their own interests and constraints.

3 Scientific issue

In the context of the interactive product design in CE, users of a DMU benefit from the multi-representation of DMU that users can work collaboratively and communicate with each other with different domain-specific representations while in unique data format.

A user is assisted by a certain tool for working. This tool provides the user a representation of DMU in certain domain; the user chooses a certain interaction manner of CHI to use this tool.

Considering the interactive user-integration during product design activities, CHI is designed for users to better interact with machines. However, in a multiple users collaborative working condition, multiple CHIs for each of the users are still barriers among users, especially when they are working in a co-located and in real time condition, e.g. a condition of project review during product lifecycle.

In real situation, each expert has one proper CHI when he/she is interacting with the DMU. When they are working in a co-located real time situation, e.g. project review during PLM, they cannot overcome the barriers of CHIs.

We could imagine if in a shared visual space, the representations of different domains are provided to different users, from the viewpoint of users, they could avoid switching eyes between two CHIs. This will help the expert to communicate and collaborate [42] with others and also to overcome the sense of isolation that happens when experts use their own tool in his laptop to attend this project review.

In a normal multiple user working situation in project review, each user has an output and input device within his/her CHI, for example, a laptop. The screen outputs (displays) DMU visual representation. This user has his/her special manners to give some input, for example different manipulation method. Since experts are working together, for example, one expert wants to add some windows on the airplane. Second expert, who is in domain of thermal, will check with his own CHI to see if the thermal constraints are limited to this modification caused by the first expert. Then he can give a response to the first expert if he can make an agreement. Since experts are co-located in the same room, it they are still working in this way, they have to wait others' responses through their CHIs. These multiple CHIs are still barriers between users. If one can minimize the response

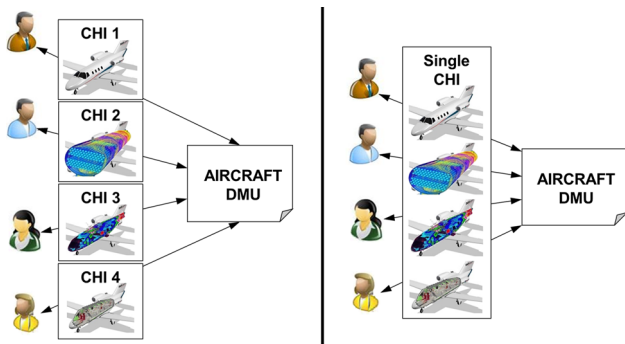


Fig. 3 *Left* multiple CHIs; *right* one single CHI replaces several CHIs may help collaborative work

delay, ideally in real time, we could imagine a co-located in real time collaboration just as a face to face communication.

How to improve the CHI system when several experts are working collaboratively in overlap activities is our scientific issue.

To enhance the collaboration among experts from different domains to work with DMU through CHI, a novel support system of CHI has been taken into consideration, as shown in Fig. 3. On the left, each user picks up his own CHI and has his own input and output through that CHI. On the right, four users adopt one single CHI to work with DMU. This mono CHI may allow different experts still to work with the tools that he/she prefers, but to get synchronized modifications in real time and to feel free to discuss with other experts in a co-located working condition.

As we mentioned in the last chapter, one single CHI mainly contains multiple visualization mechanics and multi-user interactions. According to the state of the art presented in the last chapter, we come up with the solutions of evaluations of our concept.

We first proposed several solutions for our estimated multi-view system. A glass-based approach e.g., anaglyph and polarized glasses can be used to get two 2D POVs. The glasses are formed by two original anaglyph or polarization lenses. The original two left eye lenses are now made up to a new pairs of glass, so as to the two right lenses. For our basic experiment for testing multi-view system, this may be enough.

We also proposed another two POVs approach using a collaborative polarized table that from two sides, users can be provided 3D scenes in two directions. E.g. if one stands physically at one side, he cannot see the other side of the objects in the 3D scene. The user on the other side will have the analogic feeling.

The concept of multi-interaction is further discussed before some solutions are proposed.

Multi-Interaction concerns two different aspects. The first aspect is mainly relative to multi-sensorial interaction

Table 1 Various experts interact in different meaning according to different metaphors, different object and different results [47]

Same metaphor	Same object	Same result	Multiple meanings
X	X	X	N
X	X		Y
X		X	N
X			N
	X	X	Y
	X		N
		X	N
			N

which technically needs controlling in parallel several heterogeneous interaction devices [43,44]. As far as we could imagine, 3D visualization and vision techniques, 3D sound technologies and haptic devices for force feedback, all of these devices could give the user one or more interaction metaphor with the DMU. They bring the user not only the visual perception, but also the perception of immersive sound and touching effect on virtual object [45]. Multi-interaction can support a variety of creative work for group experts' alternating activities like collaborative discussions and presentations [46]. The second aspect of multi-interaction is at interaction metaphor level: different user-defined metaphors can be conducted in real time [23].

As listed in Table 1, multiple users may firstly choose different metaphors, then use the metaphor on some objects and finally obtain some results [47]. We can estimate if the metaphors that experts chosen have a same meaning or not according to these three variances. An X is put in the table if this variance is same to multiple users. A Y is put in the table if metaphors have a same meaning. An N is put if various metaphors result in alternative meaning.

From the table, we can figure out that multi-interaction can be summarized as: One interaction metaphor can be used by different users on a same object but multiple users generate different results. This means different experts' metaphors have alternative meanings according to the experts' domains [41]. Similarly, two experts interact with the same object and get the same result. But their interaction metaphors (gestures) are different so that their metaphors also have different meanings. These two situations are also shown in Fig. 4.

For multi-interaction, according to our current device, we propose a device using motion capture technology, such as Kinect, to follow different users' motions. This device may identify several users and their gestures. We could define a gesture with which different users would get different results. Each expert could choose interaction metaphors different

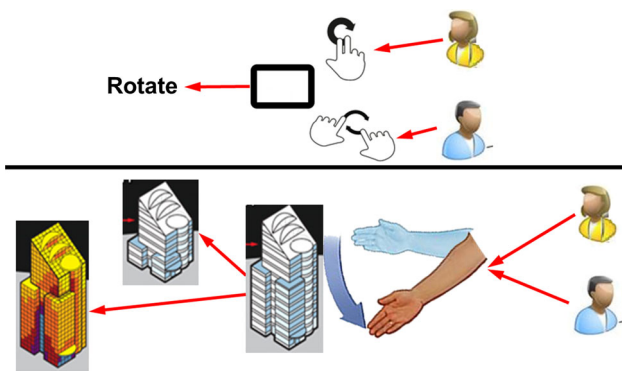


Fig. 4 Different interaction metaphors meanings: two experts interact with the same object but their interaction metaphor (gesture) may be different; one interact metaphor can be used by different experts and generate different meaning according to the experts' domains

from the ones chosen by the others in virtual navigation and manipulation of the model [42].

Our hypothesis is that multi-view and multi-interaction CHI system can support users to collaborate in co-located and real time working condition. Whether this mono CHI can really improve the collaboration efficiency or not is also to be checked by experimentation. In this paper, we conduct an experiment to evaluate the mono multi-view CHI in the chapter below with an application of a DMU-like game.

4 Experiment

As we described in the introduction section, the usability of the user interface in interactive product design may have an influence on the designers. In the co-located collaborative design activities, multiple users from different domains have to communicate in real time. Their collaboration will be effected by the collaboration tools, which is a multi-view CHI system as we proposed.

In this part, we conducted an experiment for testing whether multi-view CHI co-located supporting system is better than other solutions for multiple users in collaborate with DMU.

We propose a collaborative game to simulate a collaborative work during project review for industrial design optimization using DMU. The simulated collaboration can be repeated and certain criteria could be quantified. Regarding to the characteristics of the multi-representation of DMU, two users are displayed by two representations of one game map. They can accomplish the task in this game only by communicating respective constraints with each other. In Fig. 5, a DMU-like collaboration has its characteristics. First, this collaboration has a goal to complete and the work of multiple users can be evaluated by the completion status of the

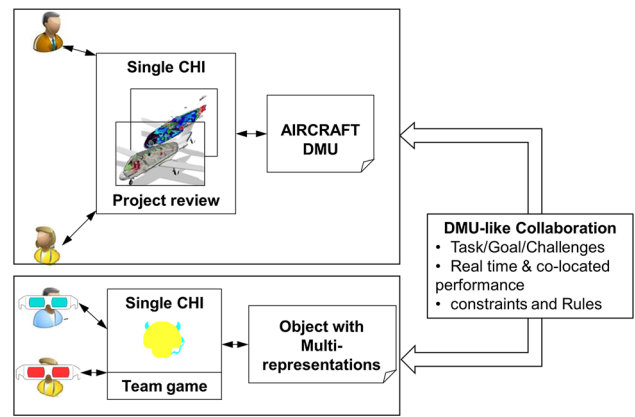


Fig. 5 A DMU-like team game simulates a real industrial case

goal. Second, this collaboration has to be co-located and has to be conducted in real time working condition. Third, each collaborator sees a special representation of DMU and has special constraints or rules from his POV. When we develop the simulation game, we have to think about these three points.

1st user is going to finish a certain task and he/she can modify what he/she sees. However, 2nd user has a restriction to respect and he/she will tell 1st user where the dangers are. We call 1st user as Player who is controlling the game character; and 'Helper' for 2nd user because he is always helping 1st user to avoid the 'Danger' by communication.

In DMU scenario, 1st user is going to modify airplane interior, but this action reaches the limit of the constraint identified by the other user, who is 2nd user, an expert in domain of structural analysis. This structure expert has to help 1st user to avoid the danger of structure crash.

Similarly, in our experiment, 1st user acted as a player, as expert in domain of searching mushroom. 2nd user acted as a helper, who is expert of searching constraints. The helper will tell the player where the constraints are.

We investigate the following hypotheses:

H1 Multi-view system provides higher collaboration efficiency. That is to say users achieve more efficiently the collaborative task using the multi-view system than without it, with less number of communications.

H2 The requirement of mutual awareness of where other collaborator is working on, or we can say the complexities to feel where other's constrains are different according to different roles of the user.

H2.1 For the user, who is a helper, the requirement of mutual awareness does considerably change across the systems (multiple CHIs, mono CHI with subdivided views and mono CHI with multi-view).

H2.2 For the user, who is a player, the requirement of mutual awareness does not change across multiple CHIs,

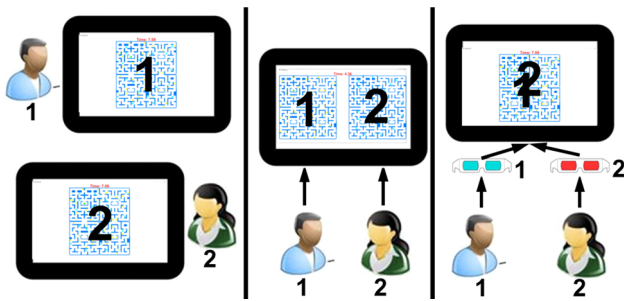


Fig. 6 Experiment conditions: separated CHIs (2Cs), CHI with subdivided views (1CSV) and CHI with multi-view (1CMV)

mono CHI with subdivided views and mono CHI with multi-view.

4.1 Setup

This experiment is conducted by a group of two users under three visualization conditions. We control independent variable of device condition, as shown in Fig. 6.

- (i) One screen for each user; multiple screens for multiple users (multiple CHIs, shorted as 2Cs).
- (ii) One screen with subdivided views and one view for each user (mono CHI with subdivided views, shorted as 1CSV).
- (iii) One screen with multiple overlapped views for each user (mono CHI with multi-view, shorted as 1CMV).

In many articles, working efficiency is defined in many ways, including time and ratio of working time to total time. In our experiment, the only thing we are searching for is that if users can make less communication to establish the task using multi-view system than the other systems. Here to define communication, we recorded all the information about communication from time, number to ratio. So in this experiment, the dependent variables that we will measure are:

1. Interactions status during the task, including time (complete time, time for vocal communication) and number (number of error, number of speaking, number of question and answer and number of active cue).
2. The requirement of mutual awareness of where other collaborator is working on. This awareness was assessed through a questionnaire after each section, inspired by [48]. The main questions are about two aspects: the first aspect asked the awareness of where other collaborator is working on. The second aspect asked the participant to estimate the awareness of the other collaborator had of the participant himself. All the responses are described concerning the satisfaction degree and feeling of time delay from 0 to 5.

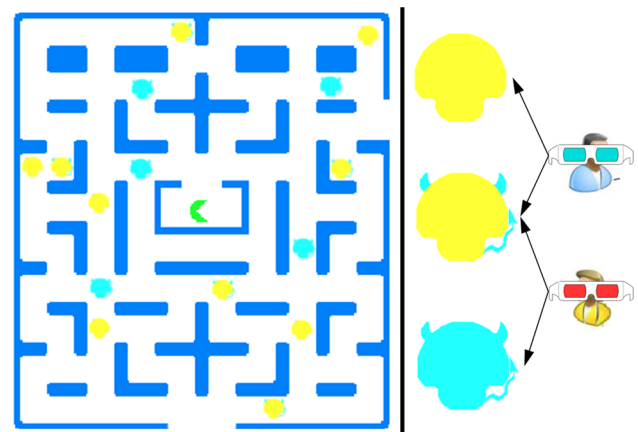


Fig. 7 Experiment map; 1st user, with *blue* glasses, can only see the *yellow* part and 2nd user, with *red* glasses, can only see *blue* parts

4.2 Task and test protocol

The task is described in details:

Pac-Devil-Mushroom The two users have to eat all the mushrooms and avoid touching as much as possible devils on the map. 1st user, 'player' with blue glasses, can only see the yellow part in Fig. 7 needs to eat all the yellow mushrooms that are shown on the left of Fig. 7. 2nd user, 'helper' with red glasses, can only see blue parts and needs to help player to avoid the right two kinds of mushrooms who are with blue color. The 'player' needs to control the Pac-man with keyboard and keep asking his partner whether the direction he wants to go is safe. The 'helper' needs to focus on the position of Pac-man and answer the question asked by player and gives player tips to avoid devils because with red glass on he can see only devils. They could hardly move unless they communicate a lot. If devils are hit, as a punishment the Pac-man will be frozen for several seconds.

Two users get different information from the map and to accomplish the task, they should collaborate by sharing the information from their own POVs. This task will be done in three visualization conditions which we have talked about in Sect. 4.1.

Each group of participants was arranged to test with three device conditions in a random order. For each condition, the initial positions of mushrooms and devils are slightly different. This is to ensure that during three device conditions, the maps are used in experiment could always be new to the participants. These slightly different maps are re-used for other groups by randomly changing the corresponding device conditions.

Before experiment, users have tried to play the game with a trial map under the three device conditions (Sect. 4.1) to be familiar with the game as well as their partner. And they could try it until they feel ready enough because for each device

Table 2 Dependent variables that measured in one task of the experiment

Time	Finish time
Time_QnA	Sum of response time that helper answers player's questions (all the question/answer pairs)
Num_QnA	Number of question/answer pairs
Time_QnA_devidedby_Time	Ratio of communication time to finish time

condition, we told them to complete the task as quickly as they can.

The three experiment conditions are in a random order to each group. After each condition, a questionnaire has to be filled in by each user.

All the experiments are video-recorded in order to record the communication time (be exact to millisecond) during gaming. Each experiment lasted on average 1.5 h.

4.3 Results

Ten groups of participants have attended the experiment. According to the visualization conditions, three sections are setup during the experiment. For each section, eight maps are conducted in collaboration. After each section, each participant is invited to fill a questionnaire separately. Each group of participants will contribute 24 games data and 6 questionnaires. We totally obtained 240 data and 60 questionnaires.

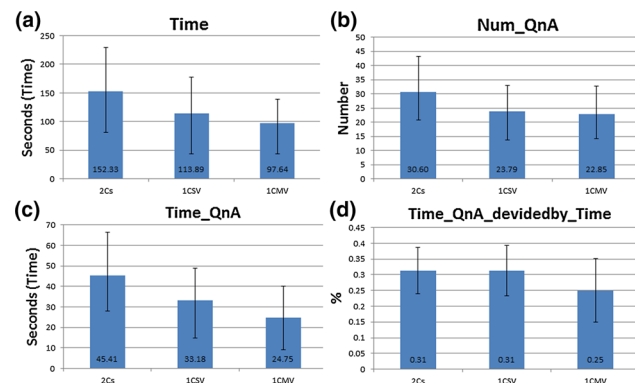
Collaboration efficiency

During a task, the different aspects of collaboration between two users could be measured. The measurements contain time, number and dependent variables. We list them in Table 2.

According to three visualization conditions of 2Cs, 1CSV and 1CMV, the mean and standard deviation of the dependent variables are formed in Fig. 8.

We can see that the Finish time [(a) Time], Number of question/answer pairs [(b) Num_QnA] and Sum of response time of all question/answer pairs [(c) Time_QnA] to complete the task decrease from 2Cs, 1CSV to 1CMV. The Ratio of communication time to finish time [(d) Time_QnA_devidedby_Time] shows that multi-view (1CMV) is better than the other two conditions.

Following the typical means of statistical principles, a test of Homogeneity of Variances is conducted [49]. We could obtain that using Levene statistic test, the distribution of data from Time_QnA respects normal distribution. We could use ANOVA for the next step analysis with Num_QnA. Meanwhile, Time, Num_QnA and Time_QnA_devidedby_Time

**Fig. 8** Average and standard deviation of the measured dependent variables: **a** time, **b** Num_QnA, **c** time_QnA and **d** Time_QnA_devidedby_Time

don't respect normal distribution. We should use Robust Tests of Equality of Means (Welch or Brown-Forsythe method) for further analyzing.

The result of ANOVA for Time_QnA shows differences in three conditions ($F(2, 237) = 27.973, p < 0.001$). A LSD post-hoc test shows that a difference between 2Cs and any of two other conditions is obvious ($p < 0.001$). The difference between 1CSV and 1CMV is obvious ($p < 0.05$).

For those dependent variables that we can use ANOVA to analyze them, Brown-Forsythe test is considered.

Brown-Forsythe tests for both time and Num_QnA have results that there existed differences among three conditions ($p < 0.001$). With correction of Games Howell method, 1CMV and 1CSV show the difference with 2Cs ($p < 0.001$). But between these two conditions, the difference is not significant.

Brown-Forsythe test for Time_QnA_devidedby_Time shows differences among three conditions ($p < 0.001$). With correction of Games Howell, 1CMV shows the difference with other two conditions ($p < 0.001$).

Awareness In the questionnaire given to the participants, the question of “How do you think the screen and maps in this experiment section support you finishing the task?” results that both player and helper feel that 1CMV can help finishing the task, more than the other two conditions. It is shown in robust tests of equality of means using Brown-Forsythe method that the differences among the three conditions are significant ($p < 0.05$). A post hoc test of Games Howell shows that the difference is significant between 1CMV and the other two conditions.

Another question of “the awareness of the unsafe positions on the map” has a result that represents the mutual awareness. For a player, there are no significant differences across three device conditions; for a helper, the differences exist in the robust tests of equality of means ($p = 0.045$). Analyzed with Games Howell correction, the difference mainly

exists between 1CMV and the other two conditions but is not strongly significant.

4.4 Discussion

Four dependent variables, finish time (time), number of question/answer pairs (Num_QnA), Sum of response time of all question/answer pairs (Time_QnA) and Ratio of communication time within the finishing time (Time_QnA_devidedby_Time), are all significant to represent the efficiency of collaboration. Both time and number during the task, as well as the communication rate, decrease from 2Cs, 1CSV to 1CMV. Obviously from our results, these dependent variables have all reached the significance levers. Users achieve more efficiently the collaborative task using the multi-view system than without it, with less number of communications (H1).

For a player who always focus on asking questions and judging the pass with responses, he may always feel unsafe and the demand of mutual awareness may always keep on a high level (H2.2). For a helper, because of the differences of the experimental device conditions, he may have feeling of different demands of knowing of player's position (H2.1). But this is not significant with multi-view CHI.

We discuss the improvement of this experiment. As an experiment of collaboration with different DMU representation, this experiment is mostly consistent with the characteristics of the real industrial case. But during the experiment, one of the user acting as helper, has only the observation of the constraints in his domain. He has not conducted a modification or a manipulation like the other user, the player. So the helper has no interaction with the DMU and the collaboration maybe unilateral.

5 Conclusion and future work

This article describes digital mock-ups property of multi-representation. DMU contains all the product information along the product life cycle in the interactive product design in Concurrent Engineering. Domain-oriented experts have different POVs of DMU so they have problems of collaboration through several professional fields. Thus, a CHI supporting platform for multiple users in collaborative design is proposed. This CHI includes primarily a multi-view visualization system, which aims at increasing vision efficiency for collaboration.

For multi-view technology, many current approaches have been discussed in both devices and applications. Each approach has its apparent advantage and drawback and there is still room for improvement.

This CHI includes then a multi-interaction system, which allows user to have certain metaphors to interact with DMU. Different metaphors used by different users result in different

meanings. This is discussed and some sub issues are proposed.

We have proposed multi-view systems progressively using anaglyph and polarization and 3D table.

An experiment with multi-view support system was carried out. Comparing to multiple CHIs system and mono CHI with subdivided views, results of the experiment indicated that multi-view CHI system has shown better collaboration efficiency. In such an interactive product design activity, this kind of multi-view CHI has a better usability in collaboration. Results of the subjective questionnaire showed that users have different demand of mutual awareness of the others. This indicates that the degree of user-integration in an interactive product design activity varies, depending on the different user roles and different degrees of contribution.

In the future work, besides current multi-view system, we are planning to use a screen-based visualization device. This device of Holografika [50] is equipped with advanced autostereoscopic technology. We plan for a solution to create more than two POVs for users.

Multi-view and multi-interaction support system is considered as part of the entire DMU CHI in collaboration. We also make a plan for a interaction method that using Kinect to recognize and interact with each other.

A prototype of proposed multi-modal interaction approaches will be developed. Experiments with multi-interaction system will be designed and evaluated. In the next design of experiment, we should also think about a bilateral collaborative working condition as we discussed in 4.4. A multi-input and multi-output platform for working with DMU more collaboratively will be realized for further work.

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