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EXPLORATIVE ANALYSIS IN A PRELIMINARY PHASE OF HYBRID VEHICLE DESIGN BY MEANS OF TANGIBLE INTERACTION

Krešimir Matković

VRVis Research Center
Donau-City Str. 11
Vienna, AUSTRIA

Denis Gračanin

Department of Computer Science
Virginia Tech
2202 Kraft Drive
Blacksburg, VA 24060, USA

Mario Đuras

AVL AST d.o.o.
Strojarska 22
Zagreb, CROATIA

Reza Tasooji
Mohamed Handosa

Department of Computer Science
Virginia Tech
2202 Kraft Drive
Blacksburg, VA 24060, USA

ABSTRACT

Simulation is used often in the preliminary design phase when there are fewer control parameters thus making it feasible to use tangible visual analysis. Tangible user interfaces and interactions are realized by deploying real objects representing control parameters. Those objects can be moved and rotated in order to interact with computer and direct the visual analysis. We can take advantage of new technologies, such as Microsoft HoloLens, to provide a mixed reality based system for tangible visual analysis. Instead of using generic tokens, as the current state of the art does, we use semantic representatives that can function without augmentation. We also introduce the iconic view, integrated within a coordinated multiple views tool, which depicts input parameters. The iconic view can be used as an alternative to the tangible interface for input parameter specification. The preliminary results indicate that manipulating simulation parameters in a less abstract way helps the experts.

1 INTRODUCTION

Design process in engineering consists of several phases which partially overlap, and which are not always executed in a strictly sequential order. A phase which precedes detailed design is often called preliminary design (Ertas and Jones 1996). During this phase, the requirements and basic concepts are already set, but it is too early for a detailed design. Overall system configuration has to be defined, and it will be refined during a detailed design phase. There are various supporting technologies throughout the design process. Simulation certainly plays a crucial role as we approach the final phases, but it is also often used in the preliminary design phase. The simulation models used in the preliminary design are often coarser than in the final design phase. There are less control parameters, and the engineers are interested in different kind of questions.

In this paper we present how tangible user interfaces (Shaer and Hornecker 2010) can be used in the exploratory analysis during the preliminary design phase in engineering. We illustrate the proposed approach on a case of hybrid vehicle design. Hybrid vehicles represent an already well established alternative to cars powered by internal combustions engines. Strict emission regulations motivate many car manufacturers to search for alternative solutions. In addition to an internal combustion engine, hybrid vehicles have electric motor as well. During the preliminary design phase engineers configure main components of such a vehicle. They combine various electric motors, internal combustion engines, transmissions, or batteries, for example.

With each new variation of a component the number of possible variations rises, and an efficient way of exploration and analysis of the design space is needed. The main idea of ensemble simulation is to run simulations for different parametrization of a simulation model and to explore results afterwards. Interactive visual analysis represents an efficient exploration method in such a case (Matković et al. 2015). The user interactively explores influence of control parameter changes on the output results in order to understand how do outputs change with changing inputs. The user also explores how to get desired (or avoid undesired) output values. During the detailed design phase the simulation parameters are fine-tuned, and their domain is usually a continuous interval. During the preliminary design phase, the parameters are coarse, the user can select one of few electric motors, for example. The parameter space is discrete in this case. In this paper we introduce a novel way of interaction for exploration of simulation ensembles in preliminary design phase. Instead of standard brushing (Roberts and Wright 2006), where the user selects a set of parameters on screen via mouse selection (rectangle, rubber-band,etc.), we propose to use tangible objects on the real desktop.

Tangible user interfaces are realized by deploying real objects which can be moved and rotated in order to interact with computer (Shaer and Hornecker 2010). In our case, the objects themselves correspond to the parameters, for example, a model of electric motor corresponds to the electric motor. If there are three variants of an electric motor which are considered in the preliminary design, there are three different models available. If three motors are of different power, the three variants are of different sizes. Now the user simply takes a corresponding objects and places it on the active desktop area (real desktop) in order to specify desired parameter configuration. Corresponding output parameter values from the simulation ensemble are automatically highlighted on the computer screen. Such a mechanism amplifies cognition by an externalization of parameter specification, the user recognizes on the first sight which configuration is selected. The preliminary design process becomes more efficient in this way. The tangible interface enables an efficient specification of input parameters. During the exploration, engineers often interactively specify output values, and they want to see corresponding input parameters. Since this is not so easy with tangible objects, we also introduce iconic views to depict input parameters. The same iconic views can be used as an alternative to the tangible interface for input parameter specification. Figure 1 illustrates the main idea and the three main components: tangible interface for input specification, interactive iconic view, and various views used for output values visualization. All these components are integrated in a coordinated multiple view system.

We, a group of visualization, interaction, and engineering experts, illustrate the newly proposed approach on an example from preliminary design of a hybrid vehicle. A very positive feed-back from the domain expert indicates the usefulness of the newly proposed approach.

2 RELATED WORK

The related work of our research covers visual analytics and tangible user interfaces. Thomas and Cook (Thomas and Cook 2005) define visual analytics as the science of analytical reasoning facilitated by interactive visualization. Interactive visual analysis (Kerren and Schreiber 2012)—a clever combination of interactive and automatic methods—has been applied to numerous domains, such as, simulation (Doleisch 2007), or time-oriented data in general (Aigner and Tominski 2007). In our previous work we provide examples of its application to engineering problems and analysis and exploration of multidimensional parameter spaces (Matković et al. 2002, Matković et al. 2011). Berger et al. (Berger et al. 2011), Booshehrian et al. (Booshehrian et al. 2012), and Waser et al. (Waser et al. 2010), for example, deal with

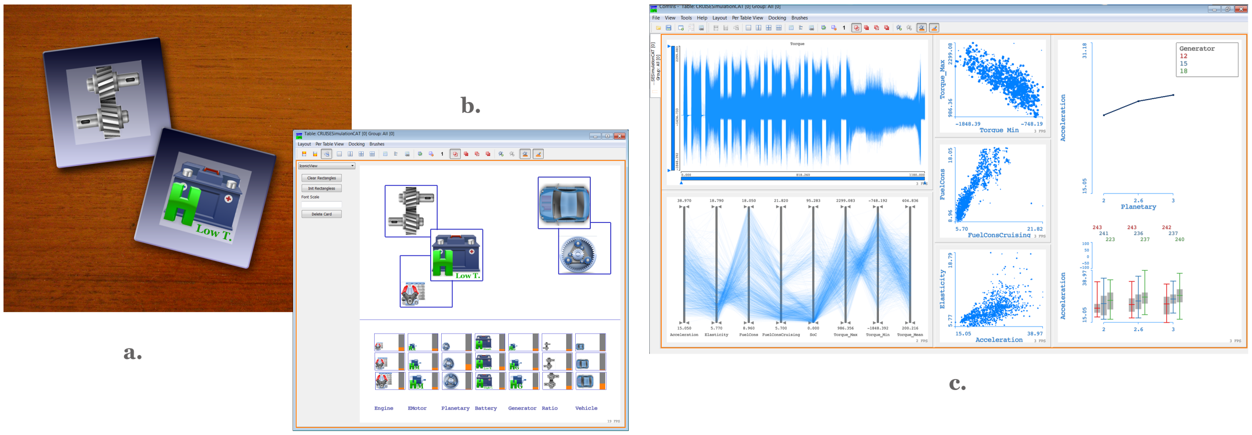

Figure 1: The three main components of the newly proposed system. **a:** Tangible 2D cards are used to specify designs. Simply placing cards on the real desktop selects some members of the ensemble, and they are highlighted in the coordinated multiple views system. **b:** The iconic view is a digital version of the tangible cards. It saves physical space on the desktop. Cards proximity determines Boolean operations between cards. **c:** A coordinated multiple views system which is used in the exploration. It reacts to the inputs from tangible cards and from the iconic view.

simulation data. Multidimensional parameter spaces are closely related to simulation ensembles. Sampling of parameter spaces has helped to solve many high-dimensional domain problems, for example, in aircraft design (Shaffer et al. 1998), or in engineering (Stork et al. 2008). Some of the authors deal with a large number of simpler responses (1D and 2D), and some focus on 3D responses (Demir et al. 2014). All above mentioned solutions use mouse and screen as input/output devices.

Tangible user interfaces (Fishkin 2004, Shaer and Hornecker 2010) have been used in numerous scenarios, on table-tops, in learning environments (Binder et al. 2004),or in virtual environments or augmented reality (AR) applications, for example (Kim et al. 2006). Virtual reality (VR) and AR or mixed reality (MR) technologies (Bimber and Raskar 2005) technologies/applications are becoming more affordable and thus more accessible to general users. While there is over forty years of research in this area, we still need more findings to better understand challenges when it comes to developing MR applications. Tominski et al. (Tominski et al. 2014) provide a survey of Interactive Lenses in visualization, including how lenses are defined, how are they used for different types of data/tasks, and what are the technologies used. The Facet-Streams (Jetter et al. 2011) are the closest to our approach. They propose to use tangible tokens in a collaborative query environment while supporting Boolean operations. Klum et al. (Klum et al. 2012) introduce Stackables, advanced tokens where each has its own display. Büschel et al. (Büschel et al. 2014) introduce transparent tokens which are augmented with a projection on table top then. Tabletop tangible objects can be used to interactively query a database (Langner et al. 2014, Jofre et al. 2015) or for interactive data visualization (Jofre et al. 2016) and information visualization (Spindler et al. 2010). They also have a great potential for improving accessibility and helping people with special needs (Zajc and Istenic Starcic 2012) or to help retrieve relevant information in a tourist spot (Camarata et al. 2002).

In contrast to the state of the art, we propose semantic tokens and use of tangible interfaces for exploration in preliminary design phase. Our target users are engineers, and the main advantage compared to the conventional input is ease of use, intuitiveness, and externalization of parameter specification which reduces cognitive load and, in this way, supports cognition.

Table 1: Component parameters which we varied in order to calculate a simulation ensemble.

Parameter	Used values
Engine	1.0L, 1.2L, 1.5L
Electric motor	25kW, 30kW, 40kW
Planetary reduction	2.0, 2.6, 3.0
Li-ion battery	Standard, Low Temperature, High Capacity
Generator	12kW, 15kW, 18kW
Final ratio	3.5, 3.9, 4.3
Vehicle mass	-40kg, Nominal, +40kg

3 HYBRID VEHICLE DESIGN AND ENSEMBLE SIMULATION

In order to use simulation we have to define a simulation model first. The model usually consists of different elements which are connected in a model. For each element different control or input parameters have to be set, and then the simulation solver computes state values or outputs for each element. In a case of a simulation ensemble, control parameters are varied and the simulation solver is run for each of the selected combinations of the control parameters. In the preliminary design phase, the control parameters are coarse, they mainly specify which component (an electric motor, for example) should be used. The main goals, however, are already known. There are power, torque and inertia requirements, as well as vehicle performance, emission and drivability which have to be fulfilled. There is usually no setting which fulfills all requirements, and engineers meet various compromises during the whole design process. In our case we deal with a preliminary-design of a front wheel drive hybrid-vehicle model. The model consists of: gasoline engine, electric generator, electric motor, battery, planetary gearbox, and differential (Figure 2).

In this design phase we vary the following components: engine, electric motor, planetary reduction, Li-ion battery, generator, final differential ratio, and vehicle mass. We decide to have three variants of each component. This results in 2,187 simulation runs, taking about 40 hours on a standard PC. Table 1 shows the values of all varied parameters.

In addition to the model parameters, a driving cycle has to be specified. The standard New European Driving Cycle (NEDC) velocity profile (1,180 seconds driving cycle) is used for each run. Figure 2 shows the velocity profile for the applied driving cycle. Three tests were conducted: the cruising test, the full load acceleration test, and the elasticity test. Out of 2,187 simulation runs which were started, 2,142 runs successfully finished. For the remaining 45 runs the target state (distance and speed) could not be reached. We do not deal with these runs in the paper.

The following subset of the computed results is used in our analysis in the analysis: fuel consumption on NEDC cycle (*FuelCons*); fuel consumption in cruising mode (*FuelConsCruising*); full load acceleration (*Acceleration*); engine elasticity (*Elasticity*); state of charge of the battery (*SoC*); and torque behind final ratio component (SRT block in the model in Figure 2) (*Torque*). All results except the *Torque* are scalar aggregates of time dependent results and the *Torque* is a function of time. We use an advanced data model (Konyha et al. 2006). This model makes it possible that one record in our data space, which corresponds to one simulation run, contains the set of control parameters from discrete parameter space, a set of scalar results, and a time series result.

4 ENSEMBLE EXPLORATION AND ANALYIS

As soon as the data is computed, the analysis can start. On a very high level, the engineers are interested in two main questions: **(1)** what is the output for a given set of control parameters, and **(2)** which parameter setting results in a desired behavior. More specific tasks include questions, such as: *"Which setting results in a minimum consumption?"*, *"Engine elasticity is very important, so how should we set the parameters?"*, or *"We would like to have a car with a high maximum velocity."*. Interactive visual analysis represents

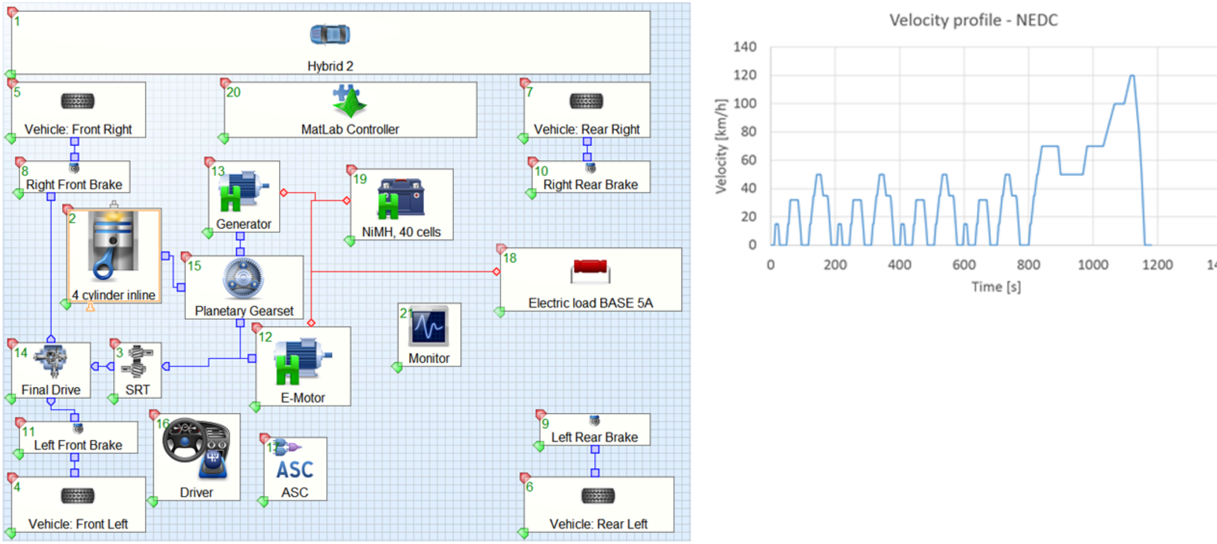

Figure 2: **Left:** The studied AVL Cruise simulation model. **Right:** A line chart showing six properties during a Cycle run test on the standard NEDC (New European Driving Cycle) velocity profile (1,180 seconds driving cycle).

a powerful solution to answer such questions, to explore the results, and to narrow down the choice of components. Final design phase will be conducted with a subset of components only.

Interactive visual analysis often relies on a well-known coordinated multiple views principle. The main idea is to depict control parameters and results simultaneously using several views, and to allow the user to brush—interactively select records in any view and to see all attributes of selected records in all other views. Figure 3 shows an example from such an analysis. The six histograms on the left show six control parameters. The views in the middle show the torque as time series, and two scalar aggregates of the torque (the minimum on the x axis and the maximum on the y axis), and, finally, the views on the right show few more scalar output values.

During the analysis, the user brushes (interactively selects) certain runs and see all corresponding values. Figure 4 depicts such a case. The user has selected high fuel consumption and a high state of charge at the same time. The brushes are visible in the histogram and in the scatter plot on the right. All corresponding runs, in all views are highlighted using orange color, and all not selected runs are depicted in gray in order to provide context information. The six histograms on the left show us which components could result in desired outputs. The user can also select components in the histograms, and see corresponding outputs.

5 TANGIBLE BRUSHING

Selection of the components used (control parameters) in histograms of any other abstract view causes additional cognitive load to a user. The user has to think over and over again which view corresponds to a particular parameter. In order to reduce this cognitive load we propose a tangible user interface. The main idea is that the user deploys tangible, real, models of the parameters, and to place them in a dedicated area on the physical desktop. The models can be 3D printouts, or cards with images on them. Figure **??** shows the main idea. In our case, the models or cards would represent three different engines, three batteries, three electro motors, and so on. Now, if the user is interested in a particular combination, she simply places corresponding objects in the brushing area on the table. All items in the system are highlighted, and a quick look at the objects immediately makes it clear what is brushed. The user does not have to carefully study abstract views, the information is externalized on the table in an intuitive way. We argue that such a system improves exploration and analysis significantly.

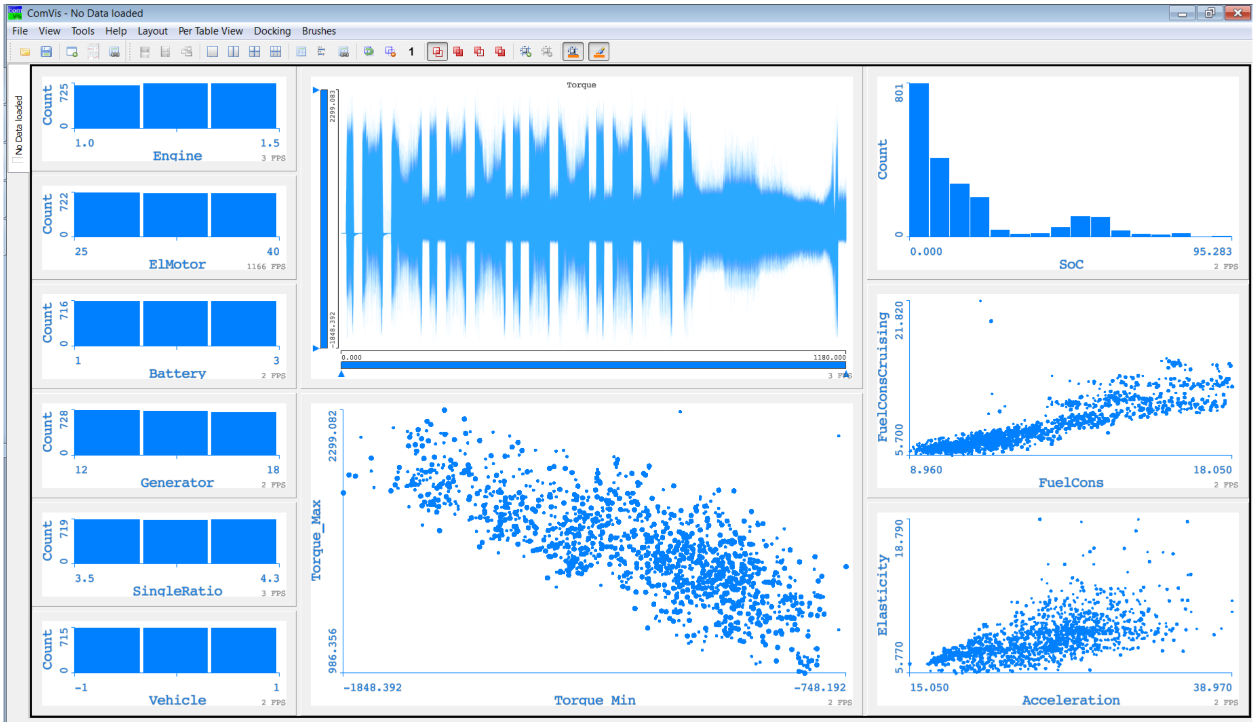

Figure 3: The coordinated multiple views system used to explore the ensemble. The six histograms on the left show the control parameters, and other views show output values.

During a usual exploratory analysis session the engineer would use composite brushing, a combination of several brushes combined using Boolean operators. In order to enable the same functionality we propose to consider tangible objects which are close to each other as “AND” operation, and far apart objects as “OR”. More complex brushes are easily created in this way.

Although the proposed extension does not require much of extra space on desktop, sometimes the available desktop space is not sufficient. We optionally replace the tangible user interface with a digital variant of the same idea. We call the new view iconic view, as we use icons instead of tangible objects. The main idea is to offer the user icons of various sizes which represent different components. Instead of three different models or cards for the engine, for example, the user sees three different icons on the screen. Now, icons are dropped to the central area in the view, and they specify the brush. The user has again a clear notion of what is brushed, and can perform analysis more efficient compared to the brushing using abstract views. Figure 5a illustrates the iconic view as used during our analysis. The user has selected following values of the parameters: a heavy car and a medium engine (on the left) OR a small engine and a large planetary reduction (on the right). The composite brushes are created in the same way as with the tangible object, the proximity defines the Boolean operation. Of course, all other views (Figure 5b) are accordingly updated. In this example the user starts the Iconic View as a separate floating window which is shown on the second monitor.

Besides reduced space requirements, the use of the iconic view has another big advantage. The engineers do specify combinations of the control parameters, but they also specify ranges or shapes (in case of curves) of simulation results. Once the desired or undesired output values are selected the user wants to see corresponding components used. In case of the tangible interface, highlighting particular objects is a very challenging task. A possibility would be to use image recognition and a set of advanced, precisely controls spotlights. Even such a settings would be probably hard to use. The iconic view solves the problem, it is easy to use it t depict which components correspond to the user selection. As there are many runs which

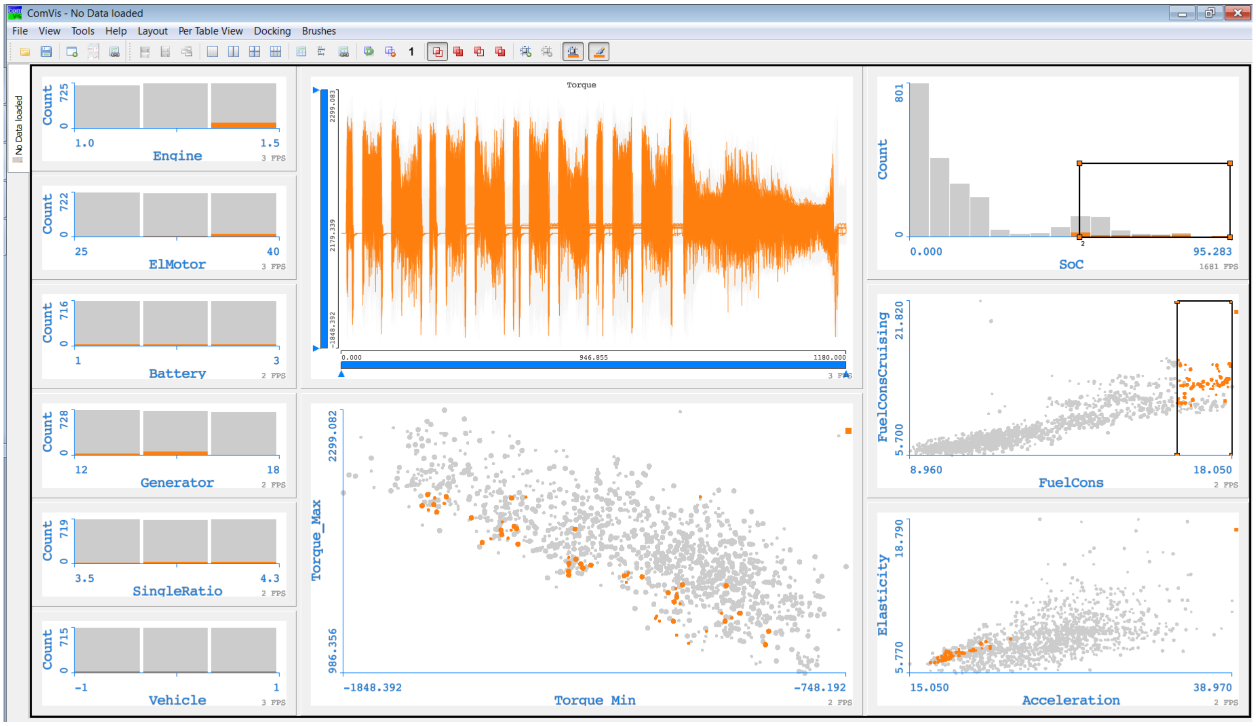

Figure 4: All views are linked—if the user selects a subset in a view all corresponding items in other views are highlighted. The user here brushes high state of charge in the upper right histogram and combines this brush with the high consumption brush from the scatter plot. All other values for selected ensemble members are highlighted in all other views.

corresponds to a single component, we propose two ways of depicting brushed data. The first depicts the amount of the brushed components in the icon itself, and the second one adds a bar next to the icon. The bars are visible in the lower part of the Figure 5a. They indicate the brushed records ratio, just as they would do in the histogram (see Figure 4). The cognitive load is reduced here as the user does not have to think which bar corresponds to which parameter.

6 PRELIMINARY IMPLEMENTATION AND CASE STUDY

We evaluate the newly proposed approach with two domain experts from automotive industry. One of them also coauthors the paper. We have already demonstrated the usefulness of the interactive visual analysis in simulation ensembles analysis (Matković et al. 2015). In this paper we focus only on the evaluation of the novel interface in the context of the automotive simulation. The studies were conducted during several weeks, and we have asked domain experts to compare the novel approach with conventional brushing. Both experts have already been familiar with the concept of linking and brushing and coordinated multiple views.

We have first tested the tangible interface. The enthusiasm of using it was really great at the beginning. Although we were not sure if engineers will like it or consider it as too playful, it was obvious from their reaction that they really appreciate it. The 2D cards are actually more appreciated than 3D models. They are easier to handle, easier to snap together for brushing, and they provide the same information. It seems there are no advantages of 3D models, except, maybe, of their attractiveness. Finally, the iconic view and its digital representation of the object is a clear long term winner. For longer analysis sessions experts preferred to use a single interface—the mouse. This is also the only interface of the three which enables linking—it shows which items are brushed in case the user brushes output values.

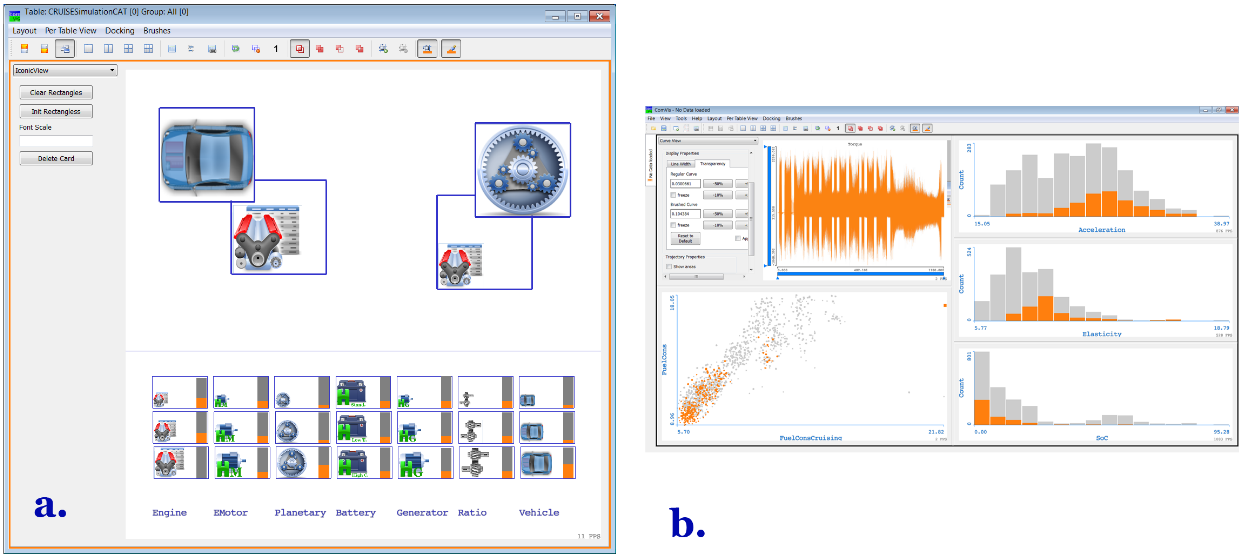

Figure 5: **a:** The iconic view is a digital representation of 2D cards. The user places the cards in the upper area of the view. The cards close together are interpreted as a logical AND combination, and groups that are far apart are interpreted as logical OR. The lower part of the view shows all available components, and the bar on the right of each icon shows the brushed data. **b:** The linked coordinated multiple views system shows the data.

Interestingly, after some time, we have talked to engineers again. One of them was convinced that the Iconic View represents a much better alternative to a collection of abstract views. He praised both characteristics: a clear notion of what is brushed in case where control parameters are used to specify the brush, and, the bars showing the linked data when brushing is performed using output views.

The second expert lost his enthusiasm soon. He is used to abstract views, and he thinks the advantages of the Iconic View are minor. It is worth mentioning that he analyzed an ensemble which is well known to him, so he did not need so much support in externalization of the knowledge he has.

6.1 Mixed Reality View

Unlike traditional graphical user interfaces (WIMP paradigm), tangible user interfaces are not well integrated. There is a cognitive and contextual gap due to the space separation between the user input and display. Various modalities of tangible inputs (e.g., AR markers, smart objects) must be integrated with a display within the user interface space. Visually overlaying tangible input with visual analysis display within the same space must address issues such as occlusion, limited embodiment and limited user interface space. We have to move beyond the 2D displays and 2D representatives to leverage benefits of embodied interactions. MR devices with integrated cameras and environment mapping capabilities can provide support for flexible 3D tangible and 3D virtual representatives. The developed system combines tangible input space with visual analysis display space (CMV tool) into a coherent and consistent MR space. The information about position and relationship between attribute representatives is mapped to a logical query representing a brush. The brush description is sent to the CMV tool and displayed in the linked views, including the iconic view.

We use Unity3D and Vuforia with attribute representatives to specify composite brushes. The requirement is that the representatives are semantically close to the dimensions they represent. Selection of one constraint is easy. However, in order to gain a full comprehension of data, composite brushing is needed. We also need other Boolean operators, OR and DIFF. All these operators should be easily combined. Based on representatives position on the screen we have to clearly interpret what the user wants to specify in the same way it is done in the Iconic view.

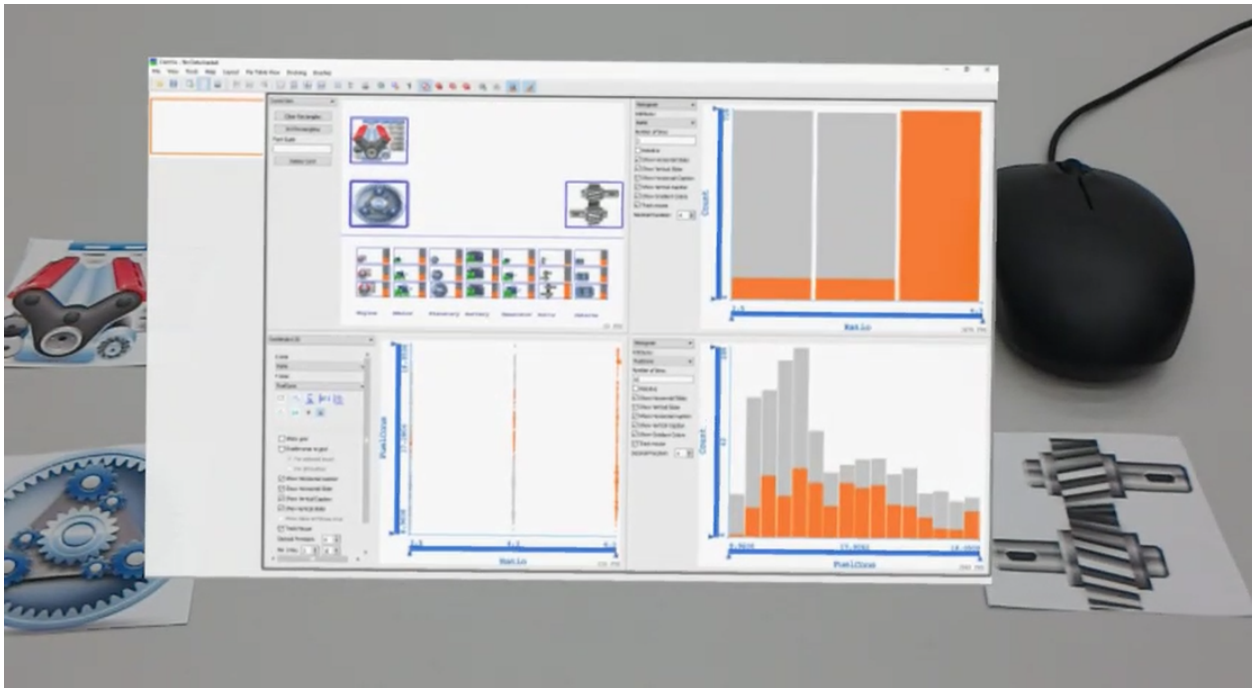

Figure 6: Tangible composite brushing in MR: a snapshot of the Microsoft HoloLens device view with the CMV tool superimposed on top of the real world view.

We rely on proximity following the Gestalt laws of grouping (Rock 1997) and interpret representatives close to each other as combined using AND, and representatives far apart as intended to be interpreted as OR. The superimposed CMV tool linked views are displayed on a computer monitor or on a Microsoft HoloLens device (thus adding the context of the surrounding physical environment, Figure 6). The user can interactively modify the brush and observe the results without switching the context and view.

7 CONCLUSION

Exploratory analysis is a powerful tool used by many experts today. The tangible user interfaces are also a well known mechanism which is rarely used by experts in the simulation domain. We have designed a system which supports exploratory analysis of simulation ensembles by means of tangible interaction and its digital equivalent — the Iconic View.

Based on our preliminary results we believe that depicting and controlling simulation parameters in a less abstract way helps the experts. This is especially true for preliminary design phase, where it is still not clear which components to use. Once the design reaches the detailed phase, with many variants and many parameters, the abstract views seem to be a better choice.

In the future, we plan to evaluate newly proposed approach in a large case study, including several data sets and several experts. We also aim at designing a collaborative interface supporting several users on one installation, or many users collaborating in a MR/VR distributed environment. Such setups are rare for experts users, and we think they represent a great research challenge. Finally, we plan to exploit our findings for publicly accessible installations as well. Exploratory analysis could be brought closer to young visitors of science museums by means of tangible interaction, for example.

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AUTHOR BIOGRAPHIES

KREŠIMIR MATKOVIĆ is a senior researcher at VRVis Research Center in Vienna. He is interested in extending visual analysis technology to challenging heterogeneous data, in particular to a combination of multi-variate data and more complex data types, such as functions. He also focuses his research on developing a structured model for visual analysis which supports a synergetic combination of user interaction and computational analysis. He teaches at TU Vienna and at University of Zagreb. He is a member of ACM, Eurographics, and IEEE Computer Society. His email address is Matkovic@VRVis.at.

DENIS GRAČANIN received the BS and MS degrees in electrical engineering from the University of Zagreb, Croatia, in 1985 and 1988, respectively, and the MS and PhD degrees in computer science from the University of Louisiana at Lafayette in 1992 and 1994, respectively. He is an Associate Professor in the Department of Computer Science at Virginia Tech. His research interests include virtual reality and distributed simulation. He is a senior member of ACM and IEEE and a member of AAAI, APS, ASEE and SIAM. His email address is gracanin@vt.edu.

MARIO ÐURAS is a team leader in the Powertrain Simulation Tool Development group within the AVL Advanced Simulation Technologies department. During his professional career he has been involved in many research and development projects in academia and industry, as a project manager or a team member. He has been actively participating in research and development within the AVL company for more then 15 years. He is a winner of the AVL Great Ideas award in 2013. He coauthored several scientific, as well as technical papers. His email address is mario.duras@avl.com.

REZA TASOOJI is an MS student in the Department of Computer Science at Virginia Tech. He received MA in Fine Art from Virginia Tech. His main research interest is bio-metric signal analysis. He studies how to explore how different stimulus can arose affects and how to use these information to create a simulation that generates affect arousal in individuals. His email address is rtasooji@vt.edu.

MOHAMED HANDOSA is a PhD student in the Department of Computer Science at Virginia Tech. His main research interest is human-centered Internet of Things, sensor data collection and visualization. His email address is handosa@vt.edu.