Some Bridging Methods towards a Balanced Design of Human-Machine Systems, Applied to Highly Automated Vehicles

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ABSTRACT

Increasingly complex technology offers benefits, but can also bring unintended consequences for users, designers, engineers or society. Most of these risks can be minimized and benefits maximized by using and constantly improving human factors design methods and concepts. In this overview article, a couple of concepts are described that the authors found particularly useful and worth being improved on the job. The concepts of design space, design space maps, design process, system Ergonomic analysis, theatre technique, and evaluation space are sketched and their applications exemplarily described for highly automated air & ground vehicles. These concepts are connected by their ability to bridge opposite aspects in the design and evaluation process, and allow designers, engineers and managers to reach a well balanced design.

Keywords: User centred design, participatory design, balanced design, wizard of oz, Theatre System, design space, evaluation space, automation

INTRODUCTION AND OVERVIEW: THE GAP IS STILL THERE

Enabled by scientific, technological and cultural progress, more and more powerful technology pushes into our daily life. In the form of information systems like computers and mobile phones, technology tries to help us to handle more information, faster, anywhere and anytime. Instantiated in vehicles, technology allows us to move faster and further. As a combination of vehicle and information technology, vehicle assistant systems and automation holds the potential for safer, more efficient and easier-to-use transportation.

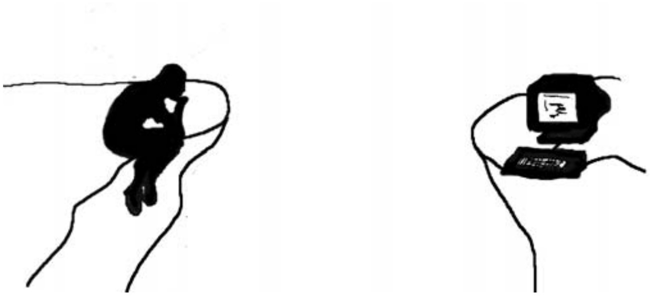

Figure 1: The gap between user and technology (Norman & Draper, 1986)

While the complexity of human-machine systems grows, the complexity that can be handled by humans is limited by their physical and mental characteristics. This characteristic of being limited and prone to errors is shared by users and development teams alike: The same moment, in which a user is unable to handle a certain complexity, in which the gap between human and technology becomes too wide and a human-machine system fails, reveals also the limitations of the design and development team to cope with complexity, and is a defeat for all of us.

To cope with this complexity, the technical, human factors and ergonomic community has worked out a rich portfolio of methods, but the choice is not easy. Quantitative methods compete with qualitative assessment, critical with constructive, scientific with pragmatic approaches. Singular effects can cause as much damage as averaging effects, but might not be properly addressed with averaging statistics. To make things more difficult, time and resources are often restricted in the design and development cycle. What is the proper mix, the proper balance of analysis methods in the design and evaluation process to ensure that assistance/automation and the human can work together in the best possible way? What methods have to be developed in order to support the development cycle?

In this article, a couple of methods are described that the authors found useful to connect different poles of the spectrum of design and engineering, and enable those poles, instead of blocking each other, to complement each other optimally. To illustrate how dynamic balance in development and evaluation of human-machine systems can work, the use of those techniques during development of interfaces for a new highly automation vehicle at NASA Langley, DLR Braunschweig and the Technical University of Munich is sketched.

CLOSING THE GAP IN THE APPLICATION DOMAIN: COOPERATIVE CONTROL OF HIGHLY AUTOMATED AIR AND GROUND VEHICLES

While in 2008, most vehicles like cars are guided manually by humans, a slow but steady revolution is taking place. In aviation, many airplanes already fly under computer control most of the time. On the road, due to intense research and development of the last decades more and more assistant systems and automation become possible, e.g. Adaptive Cruise Control" (ACC) or Lane Keeping Assistant Systems (LKAS). In the extreme, fully automated or robotic vehicles have been demonstrated in limited circumstances (i.e. at DARPA Grand Challenge).

As a combination of assistance and automation, ‘highly automated’ vehicles become possible that can drive automated in certain situations, but where the driver remains in control of the vehicle and can intervene or take over at any time (e.g. Flemisch et al., 2007). In these highly automated vehicles, a computer and a human control the vehicle together (shared control, e.g. Griffiths & Gillespie, 2005) in a cooperative way (cooperative control, e.g. Sheridan, 1992), metaphorically like a horse and rider or pilot and co-pilot (e.g. Flemisch et al., 2003; Holzmann, 2006). They even negotiate and arbitrate (e.g. Kelsch et al., 2006).

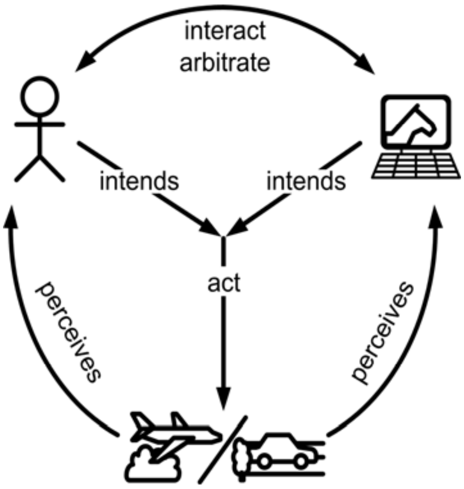

Figure 2: Cooperative control in highly automated vehicles

The design and engineering tasks for these highly automated, cooperatively controlled vehicles are not trivial: A similar development in aviation towards highly automated airplanes has brought safety gains, but also some new problems, especially with the understandability of the automation and the interplay between user and automation. This automation helps most of the time, but the gap between technology and the user can sometimes be quite wide. The design options, especially for the interface, are numerous. The following concepts helped to balance options and aspects.

DESIGN SPACE AND MAPS: BALANCING DESIGN DIMENSIONS

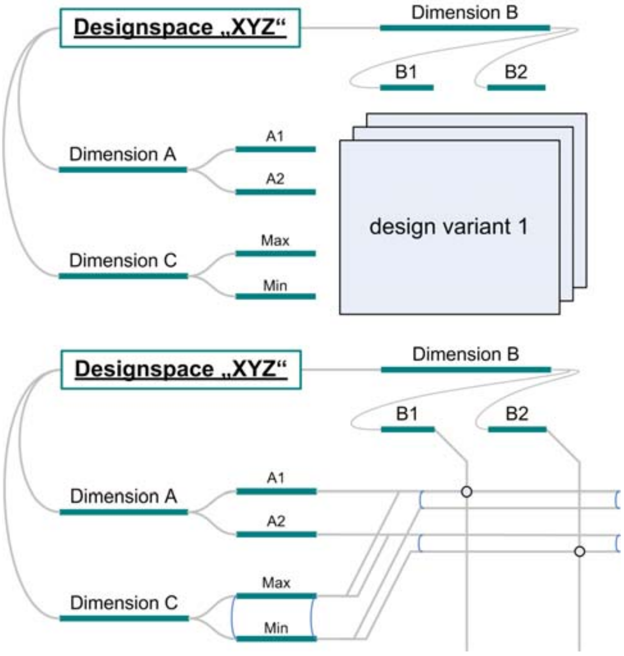

Figure 3: Mindmap and mind net map of design space

In general, designing artefacts can be quite complex, particularly when the use of this artefact has to be simple. Even if part of designing and engineering is intuitive, theory can help to mentally structure the complexity of design and improve orientation in the design and engineering process.

The concept of problem space, e.g., describes how design challenges can be structured and mapped into solutions (Simon, 1969; Newell, 1990), even if defining the problem space can be the most challenging problem in itself (Rittel & Webber, 1973). In more engineering oriented domains, the concept of design space is often successfully used, e.g. (Stankiewicz, 2000).

The design space can be structured in design dimensions, variables of the artefact that might be influenced by the designer or variables that have an influence on the designer and the design. Design dimensions might influence each other, the degree of influence or dependency varies, which corresponds to the concept of dependent and independent variables of experimental psychology.

Very often, the design space is so big that it is difficult or even impossible to calculate the proper set of independent variables and combinations that optimize a given set of dependent variables. This and the fact that resources like time, money or people are limited, makes design a creative process, where different design dimensions have to be balanced using intuition, heuristics and scientific knowledge in order to reach a successful design.

Maps of the design space can be helpful to keep track of design options. Examples include morphological boxes (Zwicky, 1974) or mindmaps (Buzan, 1991). Breaking design down into details is only one aspect, and has to be complemented with bringing details together to a whole product. This balance between the detail and the whole, between segmenting and synthesizing, can be supported by arranging the mindmap of the design space around enough space for the design, see Figure 3. In case the connections between design dimensions have to be highlighted, the mindmap of the design space can be

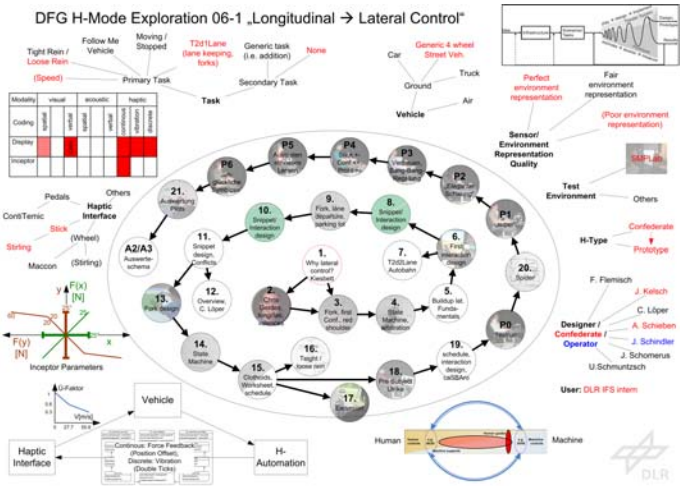

Figure 4: Application of design space and exploration map to DFG-project “H-Mode”

complemented with a net of connections, which we nicknamed “mind net map” (Figure 3).

Applied to human-machine interfacing with highly automated vehicles, the design space was built up systematically by identifying the most influential design dimensions “class of haptic interface” (Stick, Steering Wheel, Active pedal etc.), interaction channel (visual, auditory, haptic) and coding (spatial, verbal), feedback principal (force feedback, position feedback) and many more. A simple but powerful tool “Exploration map”, based on Microsoft VISIO, was developed to allow an easy logging of design activities in the design space and linking with prototypes and results (Strozek & Labenski, 2005, Figure 4). The concept and tool were successfully applied to a variety of design explorations and experiments.

DESIGN PROCESS: BALANCING TECHNICAL AND HUMAN, EXPLORATORY AND EXPERIMENTAL, CRITICAL AND CONSTRUCTIVE PERSPECTIVES

In general, design space is a more static perspective on design and development, while design process is a more dynamic perspective on moving through the design space. What is the most promising path from an idea to progress towards successfully implemented and tested human-machine systems? What are the intermediate steps (e.g. milestones)? When is the user taken into account, when shall the design team focus on technological aspects? How are analytical methods combined with creative approaches? What is a proper balance between constructive and critical perspectives, e.g. are there any intermediate tests, assessments or even experiments?

For systems with a longer history of development, the development process can be quite linear (e.g. “V”-Model see Wikipedia). For human-machine systems with a wider degree of uncertainty or freedom, more circular or spiral approaches might apply (see e.g. Boehm, 1988). Despite the necessity for transparent, comparable and sometimes formalized design processes, it becomes clear that the design process itself is subject to conscious design and adaptation. The design space of the design process also includes resources like people, methods, tools, infrastructure or scenarios that should be carefully chosen and optimized towards the individual design task.

As human factors and ergonomics have links with experimental psychology, with its strong emphasis on formalization and experimental control, it might be necessary to express that a non-experimental activity like design and engineering can nevertheless be structured and well defined. Especially for design activities with a larger degree of freedom, we found it helpful to use the term “design exploration”. A design exploration is a structured, transparent and well documented search of the design space. An exploration balances critical and constructive perspectives on technological and human factors. A design exploration can lead to one or more specific designs and/or prototypes and can lead to or include tests (e.g. usability assessments). Design explorations can especially lead up to more critical approaches like experiments, as shown further down.

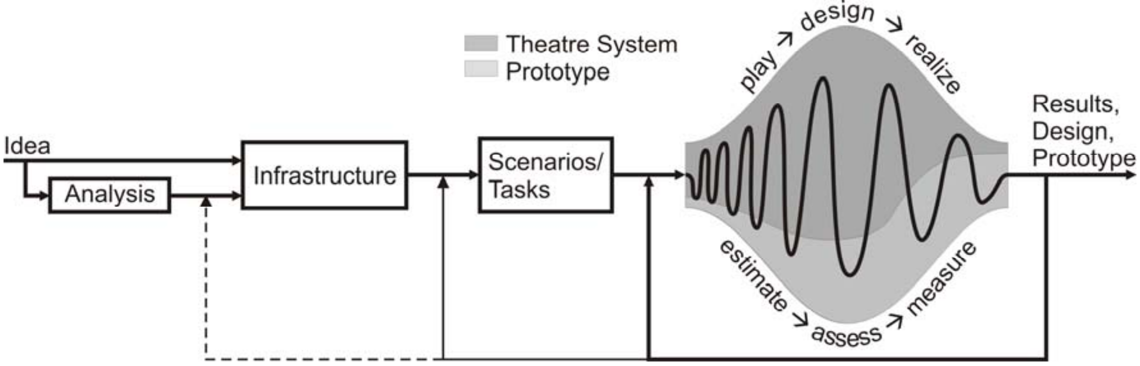

Figure 5: Exploratory design process (here with Theatre System)

Applied to the human-machine interfacing with highly automated vehicles, a exploratory design process was developed on the job that combines linear with circular aspects, and brings together elements of agile development with a more sustainable development, starting with "soft" assessments, sharpening towards critical experiments in the end (Figure 5). Starting with the basic ideas, analysis activities (like the System Ergonomic Analysis described in the next chapter) are performed, a proper infrastructure of generic simulators and increasingly complex scenarios are developed and implemented on the job (e.g. Schindler & Flemisch, 2007). With a special technique, the theatre system described below, an interplay of more constructive with more critical approaches was started. At first, design options are performed playfully, estimating and documenting the outcome. Promising features get designed, assessed, selected and condensed, until one or more design variants are implemented and tested, to include the measurement of e.g. performance. The outcome of a loop through this design cycle, including the implementation of prototypes and test results, are used to set up the next design rounds. In the last years, 5 major explorations, one leading up to an experiment with 9 subjects, have been performed based on this design process (e.g. Schieben et al. 2007).

AMENDING INTUITION AND SKILL: SYSTEM ERGONOMIC ANALYSIS

In general, designers and engineers are largely driven by technical opportunities and ideas of the user's abilities, which they try to bring together with intuition and skill. But the question is: does the user have the same internal imagination of the function of the system (so called internal model) as the designer and does the realized product correspond to this internal model?

In order to answer these questions in a very early stage of the development process, the application of system ergonomics can be helpful. System ergonomics in general is based upon the human-machine-system (Figure 6) and deals with a user-friendly design of operable and controllable technical systems and products by optimising the information-transfer between humans and machine.

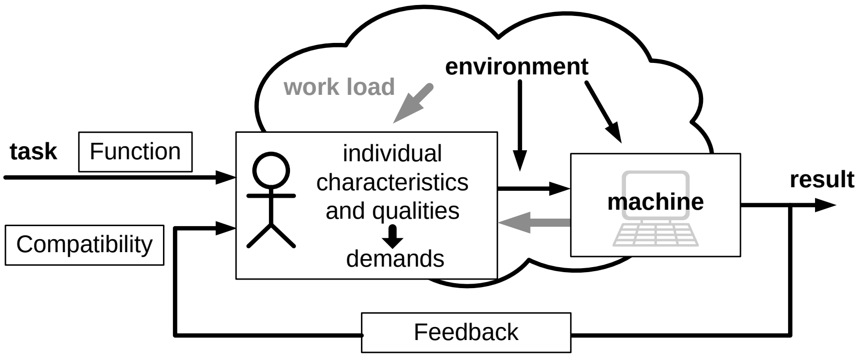

Figure 6: Schematic illustration of the human-machine-system (Bubb, 1993)

In this context the System Ergonomic Analysis is a methodical approach to analyse the properties of every task and to assign experimental experience, and from that, derive ergonomic recommendations to the partial aspects of the task (Bubb, 2003).

Every task can be described by its spatial and temporal order, which determines the task content and by elements which can be chosen by the designer – for instance the kind of the display and the kind of human influence. For the design of the task the following basic rules have to be considered, formulated as questions:

1. Function: "What are the operator's aims and how much is he supported by the technical equipment?"

2. Feedback: "Is the operator able to recognize what he has affected by his action and what was the success of it?"
3. Compatibility: "How extensive is the decoding-effort between the different information channels?"

Applied to the driving task a System Ergonomic Analysis shows the potential benefit of the H-Mode project. Regarding the first ergonomic rule, car-driving is a 2-dimensional task. Nevertheless common cars have, due to former technical restrictions, up to 5 different control elements (brake, accelerator, steering wheel, clutch pedal, gearshift) to perform this task. The result is that car driving is not a process which can be performed intuitively, but has to be learned. According to the dimensionality of the task the ideal solution in this case would be a single 2-dimensional control element (Function). To ensure the situation awareness of the driver, and his knowledge of the system's behaviour, the feedback of a system should address as many sensory organs as possible. This shows another potential benefit of the H-Mode project, as it deals with the design of a multimodal interaction-concept that covers not only visual and acoustic, but haptic feedback as well (Feedback). By reducing the number of control elements and optimizing their feedback (Figure 7), the performance of drivers - especially beginners - should improve.

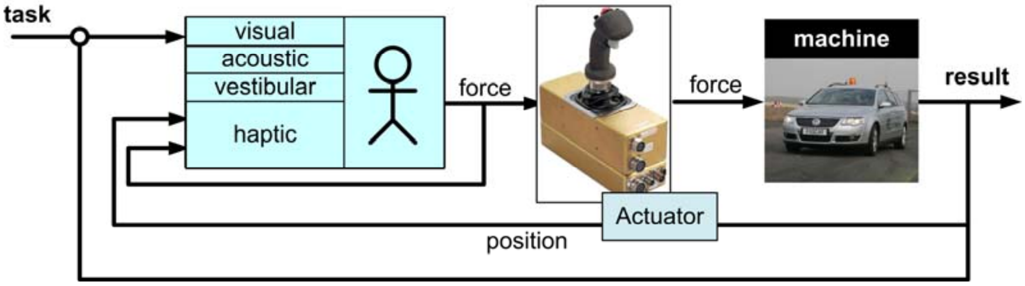

Figure 7: 2-dimensional control element with active position-feedback

This is supported by the fact that, by using a 2-dimensional control element for a 2-dimensional task, complete compatibility between handling, display and control elements can be achieved. This should lead to a decrease of decoding-effort for the user and therefore to a more intuitive handling (Compatibility). For driving with a stick, the advantages predicted by the System Ergonomic Analysis were already experimentally validated, e.g. (Penka, 2001; Eckstein, 2001). For the application to highly automated vehicles, there are already strong hints that the expected advantages will also be observed, see e.g. Goodrich et al., 2006 or Flemisch et al., 2007.

PARTICIPATORY, EXPLORATORY DESIGN IN THE THEATRE SYSTEM

In general, the development of new functionality often comes along with a large design space. While only some of the design cornerstones of this design space are hinted at analyses like the above-mentioned System Ergonomic Analysis, all the other cornerstones have to be derived from the creativity of the designers. In order to keep the gap between the outcome of this creativity and the expectations of the user small, it can be beneficial to use the creativity and the expectations of the user for design issues. Therefore the user has to be actively involved into the design process – an idea already qualified in the Participatory design dating back to the 1970s (Bødker, 1996). The most challenging part of user participation in the design process is that the know-how of the designers has to be combined efficiently to the expectations of the users.

One promising way of doing this is to simulate the aspired design by a member of the design team. In Wizard of Oz experiments, e.g., a computer interaction with the user is emulated by a “wizard” hidden behind a curtain. Because this procedure is optimized for testing unimplemented features and not for users’ design, we changed the original Wizard of Oz technique to support a design process by opening the curtain between the user and the member of the design team, and enabling her to efficiently play the automation (e.g. Flemisch et al., 2005). Design issues can be directly discussed between the user and the “Confederate”. Going hand-in-hand with this discussion, the Confederate can instantly emulate the desired features so that they can be fine-tuned at once. The obtained design can be tested as a whole afterwards by just closing the curtain. Because there is no longer a wizard who pretends to be bigger than he actually is (as in the original book by Lyman Frank Baum), but a play where both parties artfully play their part, this is called Theatre technique.

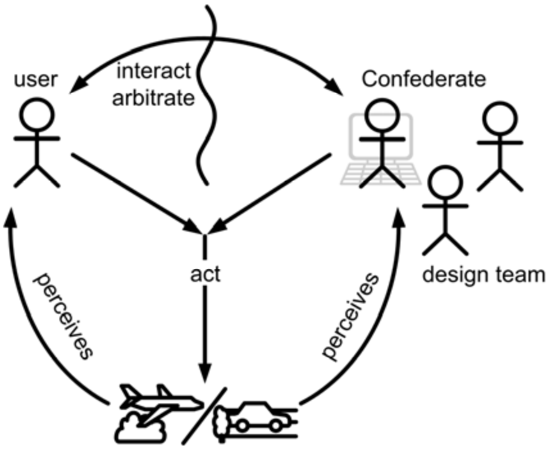

Figure 8: General setup of participatory design with a Theatre System

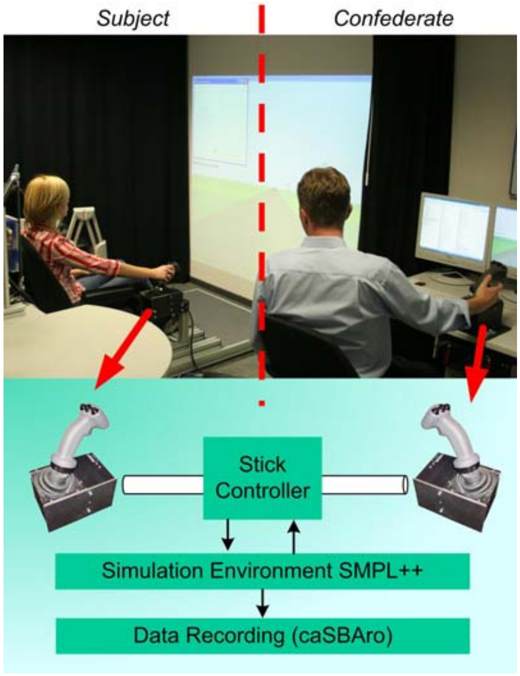

Figure 9: Theatre System for prototype design with Sidesticks

Applied to the design of automation in highly automated vehicles, a Theatre System has been realized by two like simulators located next to each other. Besides visual and acoustic interactions the respective inceptors of the user – either steering wheel and throttle, or the side-stick – are mechanically or electronically linked to the inceptors of the Confederate so that they move synchronously and a haptic interaction is possible as well. Thus, a direct and unambiguous communication via the design is realized.

For example, the following dialog could be heard when discussing the design of a haptic reaction to an unintentional lane departure:

Confederate: “What would you expect at the steering wheel when your vehicle unintentionally leaves the lane?”

User: “A movement towards the lane, maybe a vibration?”

Confederate: “How would that feel? Like this? (Conf. demonstrates a soft movement) Or more like this? (Conf. demonstrates a stronger movement”

User: “I’d prefer it a little smoother, like this...” (User demonstrates...)

This procedure has been successfully used in the design of assistance systems for longitudinal and combined longitudinal and lateral support of the driver. The design sessions in the Theatre System are repeated with at least six users per exploration. Afterwards the derived design is implemented as a software prototype and again tested with users.

EVALUATION SPACE: BALANCING INTERSUBJECT AND INTRASUBJECT PERSPECTIVES, AVERAGING AND SINGLE EVENT ANALYSIS

In general, design and engineering often starts with good intent and ends with frustrated users. Evaluating the design, collecting and evaluating data about user interaction and usability during all stages of the development process can help to control this risk. Data can be gathered during the early design phases for example by simulating a system in the Theatre System or in an usability assessment with real software prototypes. The various data sources collected can be analysed from different perspectives.

Analogue to the design space described above there is again an open space – an evaluation space - which needs to be filled. In general, the data can be analyzed in qualitative and quantitative ways. A quantitative analysis is understood as the analysis of numeric, that means quantifiable data, e.g., reaction times, handling errors or scalable questionnaire data, whereas a qualitative analysis often uses data which cannot be standardized, e.g., like verbal data of interview protocols or protocols of the thinking aloud technique. In addition, an inter- or intra-subject perspective can be chosen to analyse the data. An inter-subject approach looks for effects (differences or similarities) between subjects, whereas an intra-subject approach focuses on effects within a specific subject, e.g., on a person’s learning effects over time. Depending on the type of data an averaging statistic can be used to analyse quantitative data or a single event analysis. For a single event analysis you identify a particular event and analyze all available data sources of this event to understand it in more details. To combine the approaches described above in the data analyses opens up the opportunity to get a holistic picture of the user interaction with the system. It is feasible to start from a meta-perspective by analysing the means of the quantitative data first and then going into more detail by exploring single events. Especially, by combining explorative and experimental approaches, a very close contact with the human-machine system and its use can be combined with reliable results about the system’s quality.

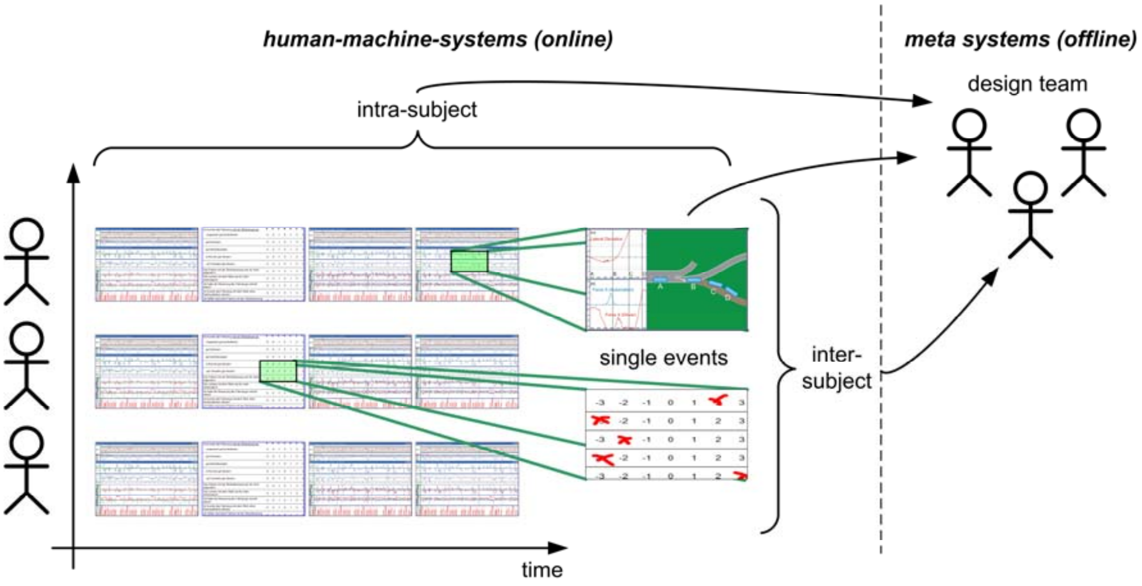

Figure 10: Schematic illustration of the evaluation process using different evaluation methods in combination

Applied to the work done in the H-Mode projects most of the analysis approaches of the evaluation space described above are covered in our usability assessments. The assessments take place in a generic simulator, equipped with a theatre system, in which normal driving situations and potential conflict situations are used to test the prototypes and the driver-automation interaction. During the usability assessments several data streams are synchronously recorded with the tool SMPL-caSBAro (“*c*omputer *a*ided *S*ituation and *B*ehaviour *A*nalysis *r*eplay / *o*nline“), that is based on the pointillist analysis (Flemisch & Onken, 2001). Quantitative data about vehicle behaviour, driver and automation inputs like forces on the steering wheel, as well as performance data on a secondary task are logged. In addition, eye-movement data can be recorded if necessary. Qualitative data like videos, questionnaire and interview data and thinking aloud protocols are collected.

For the analyses, the design team explores the interaction with the prototype by replaying the data of selected usability sessions. The replay is done with SMPL-caSBAro and allows as much immersion in the original situation as possible due to a time synchronous replay of the simulation view, videos and data graphs. During the replay specific events in the driver-automation interaction which seem to be of particular interest are marked. For example there could be a conflict situation that occurs when the driver and the vehicle automation make different choices of driving direction in front of an intersection. These specific events are analysed in detail and checked whether they occur only once or more often for different situations or subjects. If they occur only rarely we can speak of single events, if they are more often they provide an indication of an interaction phenomenon or design weakness. After the replay sessions, the data is analyzed statistically (quantitative, averaging approach from inter-subject or intra-subject perspective) or qualitatively by categorizing interview or thinking aloud protocols (qualitative approach from an inter-subject or intra-subject perspective). Some usability assessment analyses of the H-Mode projects that give an example of the evaluation strategy described above can be found in e.g. in (Schieben et. al, 2007)

OUTLOOK: TOWARDS A BALANCED DESIGN AND EVALUATION OF HUMAN-MACHINE SYSTEMS

All the techniques and tools described here were shaped on the job with specific problems in mind, but might be applicable in other domains as well. The principles behind the methods might be more fundamental: Balance is a soft but powerful concept that is successfully applied in many domains, from physics and economics to politics and beyond. Applied to highly automated vehicles, a dynamic balance between human and automation is the most promising solution. Applied to design and engineering in general, opposite perspectives like technologically oriented or human centred, constructive or critical, intuitive or analytical, quantitative or qualitative, can be combined without losing their individual edge, so that ideally every important aspect of the details and the whole can be adequately considered and a balanced design achieved. We are still far from the ideal, but will continue, in parallel to our work on human-automation systems, to foster bridging methods for the design and engineering of better human-machine systems.

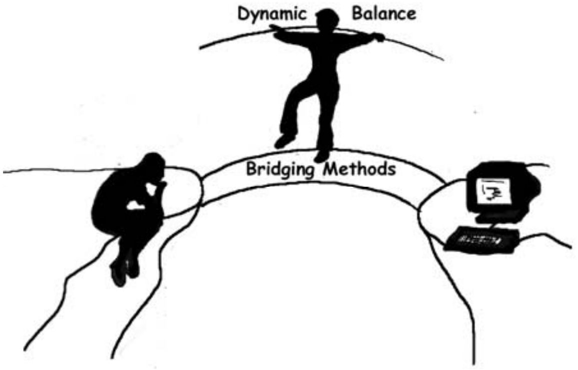

Figure 11: Bridging methods and dynamically balanced design for human-machine systems

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