Automation spectrum, inner / outer compatibility and other potentially useful human factors concepts for assistance and automation

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Abstract

Enabled by scientific, technological and societal progress, and pulled by human demands, more and more aspects of our life can be assisted or automated. One example is the transportation domain, where in the sky commercial aircraft are highly automated, and on the roads a gradual revolution takes place towards assisted, highly automated or fully automated cars and trucks.

Assistance and automation can have benefits such as higher safety, lower workload, or a fascination of use. Assistance and automation can also come with downsides, especially regarding the interplay between human and technology (e.g., Bainbridge, 1983; Billings, 1997; Norman, 1990; Sarter & Woods, 1995a). In parallel to the technological progress, the science of human factors has to be continuously developed such that it can help to handle the technological complexity without adding new complexity (e.g., Hollnagel, 2007).

In this overview article, some fundamental human factors issues for assistance and automation that the authors found useful in their daily work are briefly sketched. Some examples are described how those concepts could be used in the development of assistance and automation systems. While the article deals especially with assistance and automation in vehicles, the underlying concepts might also be useful in other domains.

From levels of automation to automation spectrum

Sometimes the terms "assistance" and "automation" are used as if they are clearly distinct or even opposite poles. In addition, some technologically brilliant developments (Dickmanns, 2002; Parent, 2007; Thrun et al., 2006) might suggest that fully automated vehicles are the "natural" follower of manually controlled vehicles and the unavoidable future. The challenge of automation is more complex, there might be solutions between assistance and automation. Which concepts could help to structure the discussion about automation issues?

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In science, there are already examples extending the common dual approach of manually controlled system vs. full automation. Sheridan and Verplank (1978) for example, expand the binary "either/or"-perspective on automation ("the computer decides everything, acts autonomously, ignoring the human" and "the computer offers no assistance") with eight more levels (e.g., "computer informs the human only if asked" or "computer suggests one alternative" etc.), and open up the discussion about a multi-dimensional design space of automation. Billings (1997) extends the automation concept such that, in addition to control automation and management automation (automation of complex management issues like navigation supporting by, e.g., flight management systems), the provision of information is already automation ("information automation"). Parasuraman et al. (2000) assign the various processing stages of automation (information acquisition, information analysis, decision selection and action implementation) as the second dimension to the continuous "levels of automation".

While the approach of Parasuraman et al. (2000) is quite helpful, essential aspects of automation might be efficiently communicated with a one-dimensional spectrum of continuous automation degrees (figure 1). This spectrum indicates the involvement of human and automation in the control of the human-machine system.

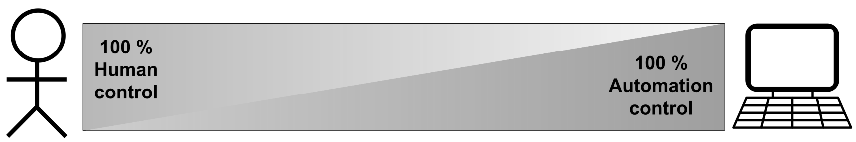

Figure 1. Involvement in system control as a spectrum between fully manual and fully automated

In this continuous spectrum different regions can be identified as assisted, semi-automated, highly-automated and fully automated control (figure 2). Control over the system might be transferred from the human operator to the automation and vice versa for all automation levels. Throughout the complete spectrum of assistance and automation similar principles of the transition might be applicable.

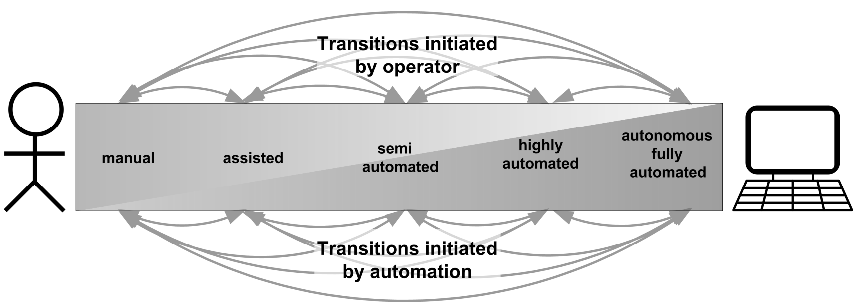

Figure 2. Automation spectrum, automation regions and transitions

This simple "map" of the automation spectrum can be used, e.g., for describing two different but related aspects:

a) The level of involvement of human and machine in the control of a human-machine system for a specific moment ("We are driving highly automated right now.").
b) The automation capabilities of a specific vehicle ("A Boeing 777 is a highly automated vehicle.").

At the beginning of the 21st century some automation subsystems in cars that influence the control of the vehicle are often called assistant systems, like Adaptive Cruise Control ("ACC") or Manoeuvring Aids for Low Speed Operation (MALSO, "Park Assistant"). For the benefit of cross-utilization of research and development efforts, the automation spectrum described here includes assistance as part of the global research and development effort of automation. Both ACC and MALSO Systems control either the longitudinal or lateral axis of the vehicles completely, and can therefore be assigned to in the region of semi-automation.

With "highly automated vehicles", research efforts in the car and truck community are addressed that go beyond semi-automated vehicles, but actively involve the driver in the control task, and link those efforts with the development in aviation, where highly automated aircraft with flight management systems have been in use already for decades.

A soft classification description for vehicle classes "Semi-automated vehicle" and "Highly automated vehicles" could be: A semi-automated vehicle has automation capabilities that allow to automate about half of the control of the movement (e.g. either lateral or longitudinal control.) Highly automated vehicles have automation capabilities higher than semi-automated up to fully automated control of the movement, where a human is usually actively involved in the control of the vehicle.

At the beginning of the 21st century, examples for highly automated vehicles are modern aircraft like the Boeing 737-400 to 777 or Airbus 320 to 380. While in 2007 highly automated cars and trucks are mainly a matter of research (e.g., Holzmann, 2006), some Japanese cars on the Japanese and UK market equipped with both ACC and LKAS (Lane Keeping Assistant System) already cross the border from semi- to highly automated vehicles. An example of a fully automated vehicle is Cybercars (Parent, 2007), where the user only communicates the destination, and from then on is a passenger.

The automation spectrum described above offers a strongly simplified perspective on human-machine systems. To design human-machine interaction in detail, especially regarding time related aspects, more precise perspectives are necessary. Some of those perspectives can be described in the Unified Modelling Language (UML), which can be expanded towards human-automation issues. As an example, figure 3 shows a sequence diagram for the transition of control from an "Automated Highway System" (AHS) to a human operator (Bloomfield et al., 1998, diagram by DLR). The diagram shows the sequence of interaction between the AHS system, covering the automation system, the vehicle and the infrastructure, and the human operator. Longitudinal and lateral control (grey columns) is transferred to the driver, after a short visual message of the system, as soon as the driver actuates the accelerator or brake pedal and steering wheel.

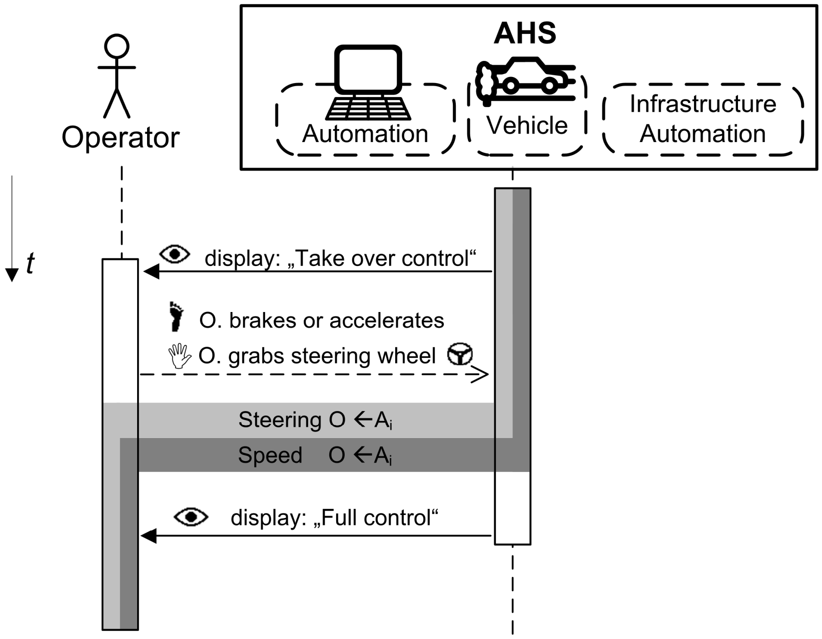

Figure 3. UML-based sequence diagram illustrating the interaction between operator and vehicle during a transition of control from the Automated Highway System (AHS) back to the human operator

Like the sequence diagram in figure 3, each of the diagrams presented in this article offers a specific perspective. Only together these perspectives open up the chance to sufficiently map, in width and depth, the territory of human-machine cooperation.

From “either/or”-automation to shared and cooperative control

The common approach for designing automated systems is to build up an automation, which perceives the environment and provides feedback or smaller control actions. The human, who also perceives and intervenes, is connected over a more or less compatible human-machine interface. When the human switches the automation on, he often leaves the control loop for this particular task. Human and automation both act on the vehicle as two relatively independent sub-systems in an “either/or”-relationship (figure 4).

The more the research and development community explores automation beyond assistance towards semi- and highly automated vehicles, the more important it becomes to think beyond classical control and thoroughly investigate relationships between the human and the automation beyond an “either/or”-relationship. Christoffersen and Woods (2002), for example, suggest designing an automated system as a team player, allowing a fluid and cooperative interaction. Of particular importance are the observability and directability of the cooperative automation. Schutte (1999) proposes using complementary automation or "complemation" in design, where complemation uses technology to fill in the gaps in the human's skills rather than replacing those skills. Miller and Parasuraman (2007) introduce a concept of a flexible automation. In this concept the operator can delegate tasks to the automation like in a human-human interaction so that the automation is adaptable to the specific needs of the human. The research of Griffiths and Gillespie (2005) deals with the exploration of a haptic control interface for vehicle guidance. In this context they use the term "shared control" to describe that the driver as well as the automation can have control over the vehicle at the same time.

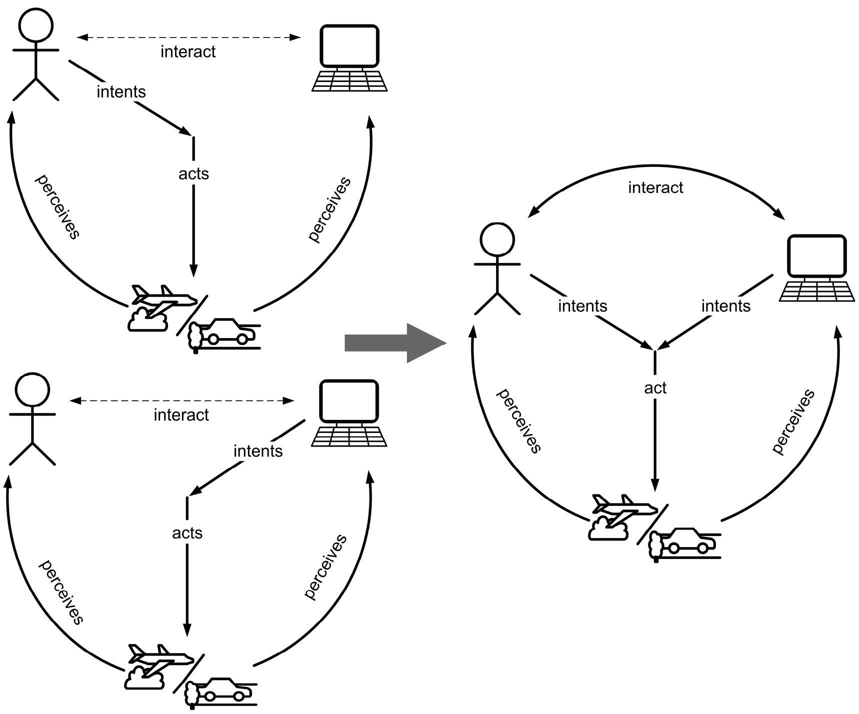

Figure 4. From classical "either/or"-automation to shared control and cooperative control

A concept that includes shared control but goes a step further can be described as cooperative control. Cooperation can be understood as working jointly towards the same goal. In 2008, cooperation in the context of vehicles is mainly used for the cooperation between vehicles. Cooperation can also be applied to the cooperation between operator and the automation, as hinted already by Onken (2002) and described for military systems by Schulte et al. (2006). For vehicle control cooperation this means that the functions which are needed to steer a vehicle are handled together and that the automation actively supports a harmonization of control strategies of both actors (automation and driver) towards a common control strategy. To enable this, the inner and outer design of the automation has to be compatible with the human and a continuous interaction has to be established. Intentions for actions are matched via a corresponding human-machine-interface and a joint action implementation can take place. Cooperative control should make the automation responsive to the driver's intentions and gives the driver the opportunity to optimize his own strategy. An example how cooperative control can be achieved is described further down.

From mental model to compatibility

Automation and assistance systems are additional subsystems in human-machine systems that could add additional complexity, especially when the level of automation is varying. Knowing what the automation does, why it does this and what it will do in the future is crucial for a successful interplay between operator and automation. Generalizing Sarter and Woods' (1995b) concept of mode awareness, this build-up of situation awareness (Endsley, 1995) about the automation can be called automation awareness. A simple system analysis of the information flow in the human-machine system shows that in order to gain and maintain situation awareness, there has to be a sufficient representation, a mental model of the automation inside the operator.

The term mental model has been used in different contexts since it was first mentioned by Craik (1943). In the context of system design and usability Norman (1983) describes mental models as follows: "In interacting with the environment, with others, and with the artefacts of technology, people form internal, mental models of themselves and of the things with which they are interacting. These models provide predictive and explanatory power for understanding the interaction" (p. 7). Therefore, usability seems to be strongly linked to the quality of the matching of the user's mental model of a system and the system functionality.

When humans interact with humans, each of the interaction partners seems to have a mental model of the other partner, whose neurological representation is, for example, described in the compelling concept of mirror cells (Rizzolatti et al., 1996). Applying this thought to human-machine interaction, a human operator builds up a mental model of the whole human-machine system and its relationships (figure 5). Similarly, the automation has to have implicit or explicit representations of its relationship with the vehicle and the environment, in order to perform its task.

The next logical step is to discuss whether a "mental" model of the automation about the operator also makes sense and is feasible (figure 5). In human-computer interaction there are already some approaches to provide the computer with information about the user. This information can be made available in an explicit way for example by user profiles or in an implicit way by the computer itself, analysing the users past behaviour (e.g., Allen, 1997).

To build up a "mental" model of an operator is not a trivial step: humans can be rather complex, especially regarding emergent effects that are much more difficult to model than deterministic effects. Moreover, if we want to use this "mental" model as a basis for building up an adaptivity of the automation this can add an additional complexity to the overall system and to the mental model of the operator, especially when the adaptivity of the automation meets human adaptivity. However fruitful such approaches will be in the future to add a "mental" model of the operator to the automation, there is a clear priority: good design of artefacts should at first enable humans to build up and maintain a sufficient mental model of the artefact and its use, before it might enable the artefact to build up a "mental" model of the human.

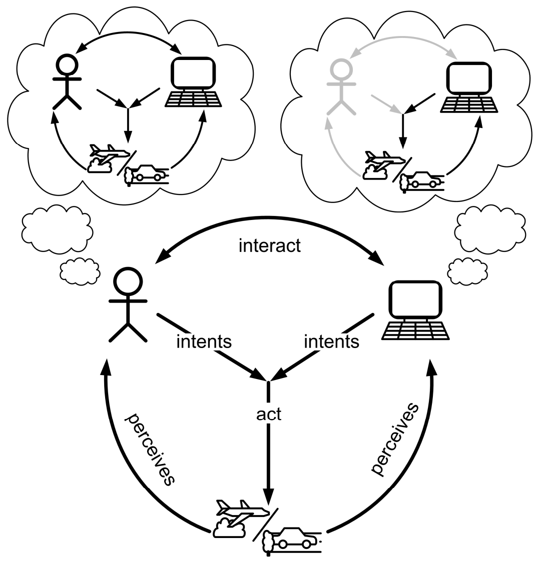

Figure 5. Mental model in human and "mental" model in automation

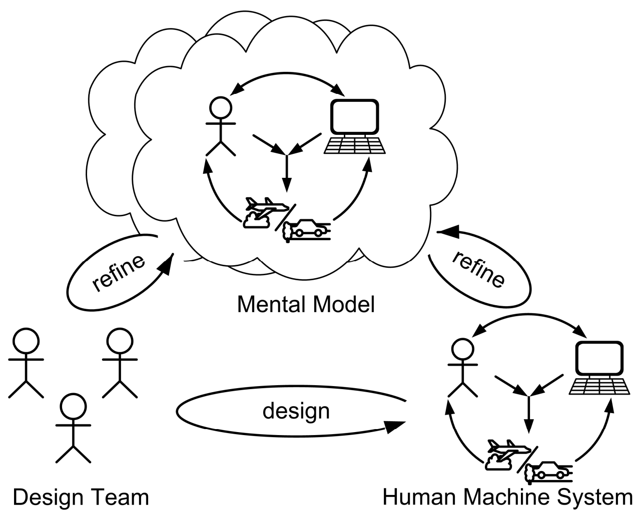

Figure 6. Shared mental model in the design process

If we go back one step further and look beyond the human-machine systems, mental models are also a useful concept in the design process: good design does usually not fall out of the sky, but derives from the hard work of many people in the design process. A key challenge here is to develop, refine and communicate a common and clear "picture", a shared mental model of the future human-machine system early enough in the design process (figure 6). Many shortcomings in the design seem to be related to shortcomings and discrepancies in the mental models shared within the design team, and with future users of the human-machine system. An example later in the article will illustrate how the build-up of a shared mental model can be supported with a "seed crystal".

Back to the human-machine systems: Norman (1988) defines the terms "Gulf of Execution" and "Gulf of Evaluation" and illustrates that the fitting of the mental representation of the user and the physical components and functionality of a system is essential for good usability. The term "Gulf of Execution" describes how well a "system provides actions that correspond with the intention of a person", whereas the term "Gulf of Evaluation" focuses on feedback issues. It is defined as "the amount of effort a person must exert to interpret the physical state of the system and to determine how well the expectations and intentions have been met" (p. 51). For a more detailed discussion on gulfs and distance between humans and machine see Schutte (2000). While "Gulfs" are stressing the distance between humans and machine, the concept of "compatibility" described in the following paragraph stresses the necessary matching of humans and machines.

Inner and outer human-machine compatibility

Compatibility is a quality describing the fit or match between two entities. Human-automation compatibility is a subset of human-machine compatibility and specifies how easy it is for the user to interact and understand the actions of the automation in each situation. Bubb (1993) describes compatibility as the effort a human needs to recode the meaning of different information. High compatibility leads to a reduction of recoding effort. He differentiates between "outer" compatibility as the correct fit of the interfaces between human, machine and reality, and "inner" compatibility as the fit of the operators' mental (inner) model with the perceived information via the operated machine. Based on Bubb's definition, the notion of compatibility can be broadened:

Outer human-machine compatibility describes the fit of the outer borders of the human (such as their eyes, ears and hands) with the outer border of the machine (the hardware interface). This means for example that the machine only uses signals for interaction that are in the range of human sensors. Moreover, the inceptors of the machine, e.g., buttons and levers, should be designed in an ergonomic way. Many issues of outer compatibility are addressed in the field of classical ergonomics.

Inner human-machine compatibility can be defined as the match or fitting of the inner subsystems of the human with the inner subsystems of the machine. Coll and Coll (1989) for example describe a cognitive match, which can be reached by "making the system operate and interact with the user in a manner which parallels the flow of the user's own thought processes" (p. 227). This cognitive match is essential for usability. A cognitive match or cognitive compatibility is one part of the inner compatibility, but not the only one: other parts of inner compatibility are emotional compatibility, and compatibility of values and ethics, concepts that have been hinted by science fiction (e.g., Asimov, 1950), but still have to be explored in the science of human factors.

Compatibility does not necessarily mean similarity or even equality: in the same way as a power outlet and a power plug are different, but compatible, humans and machines can be different, but should also be compatible. The concept of human-machine compatibility described so far offers a well defined boundary between inner and outer compatibility, i.e., the outer border of the human and the machine, but also stresses that inner and outer compatibility belong together inseparably: overall human-machine compatibility is the product of inner and outer compatibility. Sufficient compatibility between humans and machines can only be reached, if there is enough outer AND inner compatibility.

Automation roles

Thinking about mental models and inner or outer compatibility can help us design human-machine systems, but might not be sufficient, especially when machines get more complex. In human-human relationships, additional concepts have proved to be helpful, and might cautiously be applied to human-machine relationships.

In literature, there are already concepts dealing with the role-sharing between human and automation within a human-machine system and the design of this role-relationship. Billings (1997) pointed out that "responsibility" and "authority" are two very important characteristics in the design of a human-centred automation. He discussed the problem of "limitations on pilot authority" and pointed out two types of such limits as part of a special design space: "hard limits" and "soft limits". A role includes responsibility and authority but might cover also more aspects: Linton (1979) defines the social role as an entirety of all "cultural models" attributed to the given status (e.g., mother, boss). This includes expectations dependent on the social system, values, patterns of activity and behaviour. A social actor has to rise to these requirements according to his position. Altogether, a role is a multi-dimensional construct, in which parts of it can be dependent on each other. Similar to the automation spectrum described above this multi-dimensional construct can be mapped to a one-dimensional role-spectrum (figure 7).

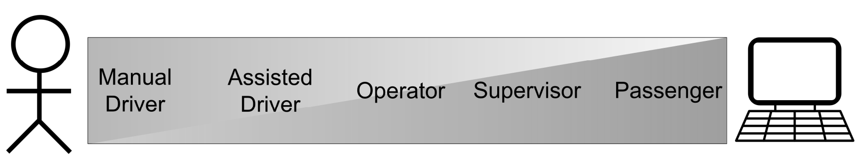

Figure 7. Potential role spectrum in vehicle assistance and automation

While the potential of role concepts applied to automation still waits to be exploited, one way to create explicit roles is the use of metaphors in system design. A metaphor serves both the designer and the user to understand the possible diversity of roles and of the related complex system easier and quicker.

Example: cooperative, manoeuvre-based automation and arbitration

The following section gives a brief overview of the concept of arbitration and cooperative, manoeuvre-based automation, which implement the common concepts of cooperative control and compatibility.

What happens if human and automation, both intervening in the vehicle control, have different perceptions of the situation or different intentions? An example would be a road fork, where the human wants to turn to the left and the automation right. Such conflicts between human and automation have to be resolved. The human-machine system must achieve a stable state, in which a clear and safe action can be executed. Time is often a critical factor. Griffiths and Gillespie (2005) already speak about the "collaborative mode of interaction"(p. 575) and a need for negotiation between human and automation suggesting a kind of human-machine haptic negotiation on the same control interface. To achieve this, a concept of "arbitration" can be helpful, i.e., a fast negotiation between human and machine about cooperative actuator access with the aim of reaching a "joint will" and a "joint action" (Kelsch, 2006). The concept of arbitration uses dialogue rules and psychological conflict solving approaches as described for verbal and non-verbal human-human and human-animal communication. Arbitration can be enabled implicitly by an appropriate design of the automation and the interface, or explicitly with an arbiter, a specialized subsystem of a cooperative automation that moderates the negotiation between human and automation and if necessary makes an equitable decision in a time-critical situation (figure 8).

To enable the described arbitration process the underlying automation has to be cooperative. Which specifics are needed for the design of the cooperative automation? The automation has to generate action suggestions and rate these suggestions. Within the discussion process with the human via the interaction the action intentions may be modified or revaluated. Finally the common action intention has to be prepared for execution. Since there is now a common intention about what to do, the proportion of control can be dynamically distributed between human and automation, a common action implementation can be executed.

To facilitate the cooperative handling of vehicle control an automation structure is needed which allows the discussion and the generation of a joint driving strategy. To achieve this, the concept of inner compatibility described above is employed. Figure 8 shows one way how cognitive compatibility (part of the inner compatibility) of human and automation can be increased. For the human information processing some aspects of the models of Donges and Naab (1996), Endsley (1995), Parasuraman et al. (2000) and Rasmussen (1986) were combined and simplified. This basic structure can also serve as the basic "cognitive" structure for the automation. Firstly, the automation module "perception" generates and process sensor data about the environment. After this, the module "situation assessment" builds up a situation representation which serves as basis for the following processes. Intended actions are generated on four levels in continuous communication with the operator.

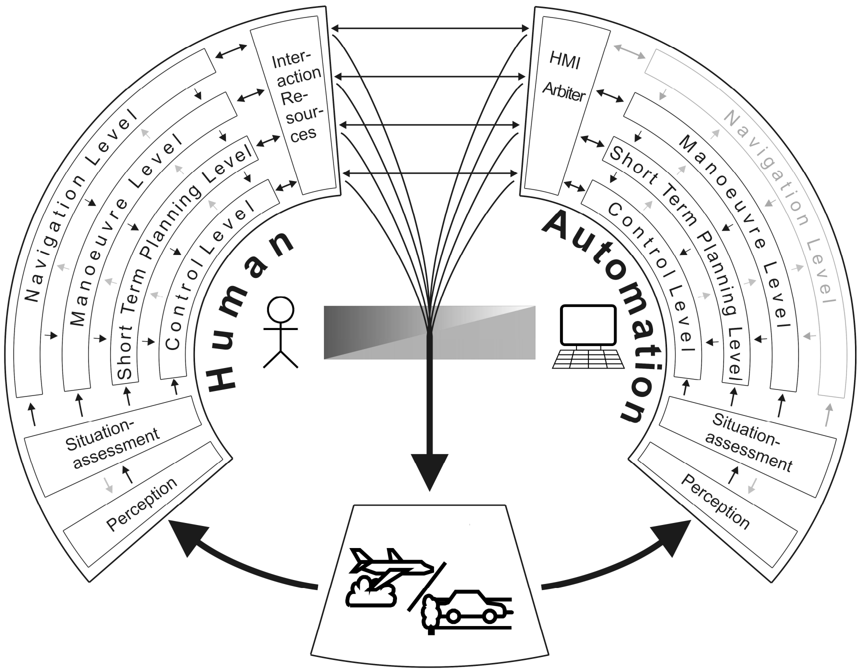

Figure 8. Cooperative automation and arbitration

The navigation level is used for planning a route for the vehicle through the road network to reach a certain destination. The next lower level is structured in manoeuvres, time and space relationships that are also meaningful to the operators / drivers. Manoeuvres are, for example, "follow right lane!" or "overtake!". The short term planning level provides a trajectory for the vehicle movement for a short period of time. Based on this trajectory, the control level generates control actions that are fed to an active interface and are combined with the user's actions.

Based on the experience with cooperative control so far, it seems to be essential that the loop between human and automation is closed and maintained on all four levels simultaneously. This closing should be in a way that allows the human to fluidly change his focus to one particular level without loosing track of the other three. This also opens up the option of a "Fluid Automation", a special form of adaptive automation, where the automation "flows" into those levels that are currently not in the focus of the human (P.C. Schutte & F.O. Flemisch, personal communication, November, 2002).

There is a good chance that a structure of the automation similar to the operator's understanding of the task, combined with an explicit arbitration, leads to a higher inner and outer compatibility and therefore to a better interaction and cooperation between human and automation. It is important to keep in mind, that even if the internal structure of human and a cooperative automation might look similar, e.g. in figure 8, and even if there are cooperative design metaphors like an "electronic co-pilot", this does not necessarily mean that the automation has to be human like. Capabilities and implementation can be vastly different, as long as human and automation are compatible, as shown in the next chapter.

Example: H-Metaphor, a design metaphor for highly automated vehicles

An example where all of the concepts described above come together is the H-Metaphor. A metaphor applies a source (e.g., a natural example) to a target (e.g., a technical artefact), creating something new. An example for a design metaphor is the desktop metaphor, where the concept of an office desk is applied to the surface of a computer operating system, creating a "computer desktop". Another example in the domain of vehicle automation is the H-Metaphor, where the concept of horseback riding/horse carriage driving is applied to the haptic-multimodal interaction (H-Mode) with highly automated vehicles (Flemisch et al., 2003; figure 9). One potential benefit of a design metaphor is that it provides an easy to communicate seed crystal for a shared mental model between the members of a design team and the operators of the designed system.

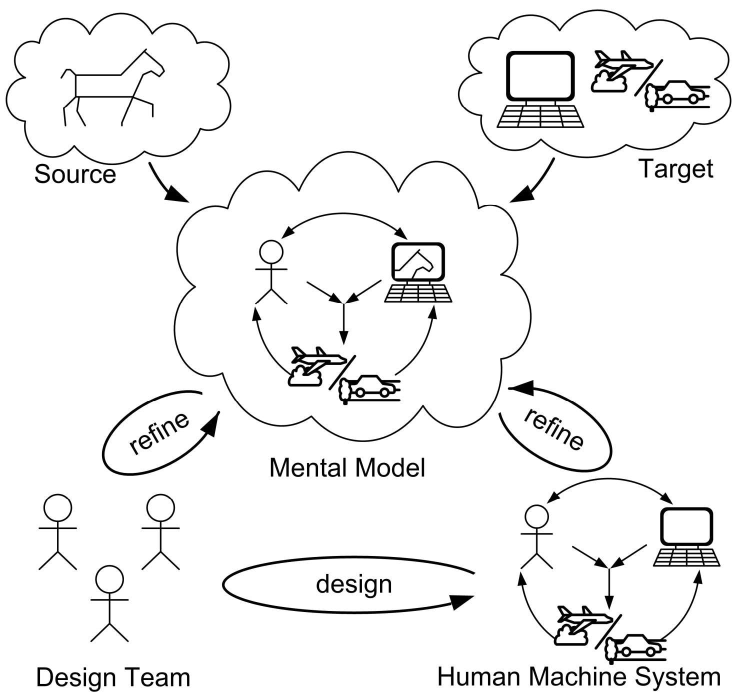

Figure 9. Design Metaphor as technique to create shared mental models (Example H-metaphor)

The H-Metaphor also describes levels of automation (tight rein / loose rein), cooperative control with a mix of continuous and discrete interaction, the transitions and the general role of the operator (figure 10).

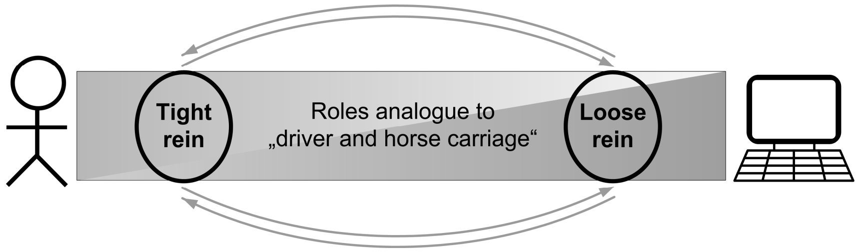

Figure 10. Automation and role spectrum described by the H-Metaphor

Arbitration, as sketched in the last chapter, has been implemented as a fast haptic-multimodal negotiation between human and machine, similar to the communication between human and horse.

The H-Metaphor has been applied to wheelchairs (Tahboub, 2001), to aircraft (Goodrich et al., 2006) and to cars (Flemisch et al., 2007), with a far reaching goal to develop a universal, haptic-multimodal language (H-Mode) for the interaction between humans and highly automated vehicles at all.

Assistance and automation: a risk, a challenge and a chance, also for human factors

At the beginning of the 21st century, technology pushes strongly towards more complex assistance and automation. This is a challenge, a risk and a chance for all of us, and especially for human factors. On the one hand, if human factors would only use the mindset and methods of yesterday to solve the problems of today, it would inadvertently contribute to the complexity of tomorrow and would be in a strong dilemma, as Hollnagel (2007) puts it. On the other hand, if and only if the human factors community continuously develops appropriate mindsets and methods in close coupling with solving the problems of today, there is a realistic chance that human factors can help to handle the complexity of tomorrow, and can make a difference.

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