Contribution to 30th European Annual Conference on Human Decision-Making and Manual Control (EAM 2012), 11. September 2012, Braunschweig, Germany

Using human-compatible reference values in design of cooperative dynamic human-machine systems

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Introduction

The design of cooperative dynamic human-machine systems, such as driver assistance systems within a vehicle being part of the traffic, is a challenging task. The result has to be easily comprehensible for the user, although the overall system complexity might be rather high. Firstly, the driver assistance systems are able to perform a complex but partially hidden behavior. An Adaptive Cruise Control system (ACC), for example, can perceive relevant aspects of the current traffic situation and can decide autonomously about the longitudinal maneuver, such as approaching or maintaining speed. In parallel, it performs singular actions, such as deceleration to avoid collisions. However, the matching of technical and design constraints of the machine behavior and natural human behavior can be difficult, particularly in time- and safety-critical situations, for instance during emergency braking or evading. And secondly, the overall system complexity increases caused by the high number of different assistance systems already on the market. In some cases they are not well integrated and the driver has to interact with each of them separately. To design well usable cooperative dynamic human-machine systems and interaction, a usability improving and system integrating approach is required. In this paper, we describe such an approach based on the use of human-compatible reference values. The main reference value that we use in the design of driver assistance systems is named ‘action tension’. We show exemplary how such a value can be derived from well-known and accepted scientific concepts, how it can be operationalized and evaluated within a usability assessment and how it can be used in the design of an integrated driver assistance system in case of an approach, brake and evade driving scenario.

Theoretical background

From the technical perspective, a cognitive system consisting of at least two agents, e.g. a human (H) and a machine (M), where both are able to control simultaneously a technical artifact, e.g. a vehicle (V), embedded in an environment (E), can be described using a simplified control diagram as shown in Figure 1-1 (left). The human as well as the machine perform tasks to achieve goals, e.g. movement in space avoiding collisions. There are at least five closed control loops. The human as well as the machine perform intended behavior by communicating their states ($State_H$, $State_M$) and actions ($Action_H$, $Action_M$) to an interaction module, which provides a joint action ($Action_J$), which controls the vehicle, and two feedback signals ($Feedback_H$, $Feedback_M$) closing two inner loops. The human as well as the machine perceive the outcome of their joint action in terms of vehicle and the environment states ($State_V$, $State_E$), which close two further loops. The outer-most loop is closed when achieved results modify the input tasks and goals. Although there are five closed loops, we do not yet find any explicit controller unit in this control diagram, which is a common characteristic in a human-machine system. Of course, the human is usually able to control the system using perception, mental models of the tasks, necessary actions, machine behavior and the control process (driving) itself. The machine also can be equipped with an automation considering the human [8] and the human-machine interface as control path. Within the interaction module, we can use control arbitration strategies [6] and action oriented information and warn strategies [11]. The synchronization of these two ‚hidden controllers’ usually only occurs indirectly via the feedback. This could result in the suboptimal system stability and robustness and subsequently the suboptimal usability.

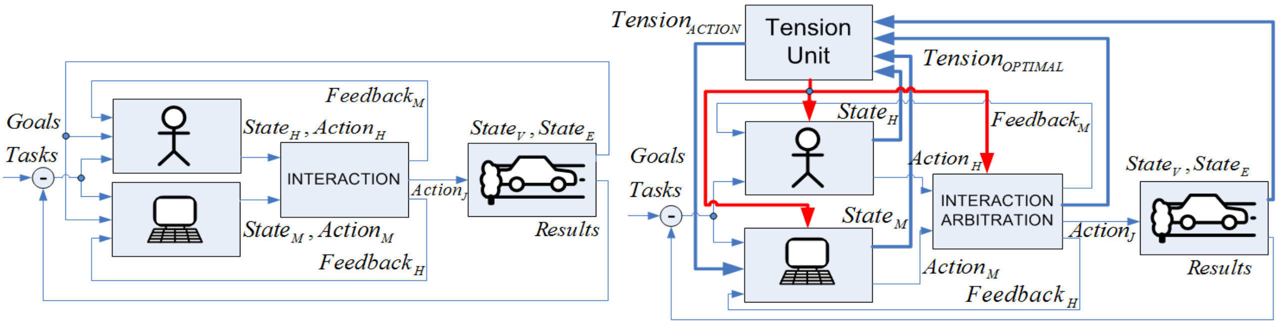

Figure 1-1: Common control diagram for a human-machine system configuration in automotive domain (left) and modified control diagram after application of the tension approach (right)

Let’s change from the technical to the psychological and the human factors perspective. Theories and models from the fields of cognition or motivation research provide a set of useful concepts to describe human motivational and information processing, behavior and their links. Lewin [7], for example, argues that a human, being in a particular physical or mental state, is experiencing ‘outer’ psychological forces, which cause locomotion toward another state. Lewin names the ‘inner’ forces causing locomotion *tensions*. For example, if we are in the state of ‘being hungry’ then we are drawn to perform actions in order to get some food and to reach the state of ‘being full’. Within the ‘Ecological Approach’, Gibson [2] introduces affordances as an object quality opening ‘action opportunities’ interfering with the actual human state. So, if we are tired and see, for example, a chair, the object chair is affording, ‘pulling’ us to sit down. Both theoretical concepts operate with terms being near to physical and technical terms like force and tension. These concepts provide the opportunity to model the behavior of humans and machines both on a higher level and on a common ground. The complex interaction processes, being highly dependent on human and machine behavior themselves, can be modeled in a more simplified manner.

The higher-level concept of tension can be used to compose reference values for description, harmonization and control of inner processes for entire cognitive systems, such as multi-agent or human-machine systems. **Thesis:** a cognitive system being in a particular state can be described as controlled by multiple tensions directed toward actions leading to other system states. So instead of using, for example, the usual values like reference path or speed for vehicle control by the machine, we can use more composed human-compatible values. These could be, for example, an appropriate situation criticality description modified for higher level control by values such as human attention and control involvement state and machine ability and uncertainty state [5]. Such reference values would describe the signal flow within a human-machine system in a way that can be easily communicated to the human user as they are related to the human user's everyday experience. Furthermore, as these values are compatible with human behavior and its underlying psychological processes, they can be transferred into human-machine interaction concepts easily understood by system users. Therefore, this allows creating a transparent system without losing required features for precise control of the system, for example, in a form of a model predictive controller.

In the human-machine design for driver assistance systems we use a reference value called *action tension*. We define it within the human-machine system as a *directed* motivation (tension) toward a particular action. It is a *composed* value depending on external as well as on internal factors referred to the human-machine system boundary. The external factors are dynamical effects and constraints that are in general outside of a human-machine system, e.g. the dangerousness of the situation, legal and other external requirements. The internal factors are inside of the human-machine system. These are the actual and planed human and machine actions, states and constraints, e.g. human factors, vehicle dynamics, preferred control actions of the human and the machine. Action tension can be fragmented (e.g. into longitudinal, lateral, assistance mode transition tension) in order to control and synchronize corresponding behavior (longitudinal, lateral moving actions and the choice of the assistance mode).

The basic idea behind using action tensions for the control of a human-machine system is the **hypothesis** that humans are supposed to aim at keeping the tensions in an optimal state and machines can be designed to do so as well. For example, neither human nor machine collide usually with obstacles performing actions toward safe human-machine and traffic states. They obey rules and laws and try to stay in an optimal condition (e.g. attended) while performing intended or allocated tasks. The optimal tension can be given by a former design decision, for example, using Yerkes-Dodson law [12], or arbitrated [6] dynamically. We define action tension as a function of human, machine, vehicle, environment state and the optimal tension:

$$\vec{Tension}_{ACTION} = f(State_H, State_M, State_V, State_E, \vec{Tension}_{OPTIMAL}) \quad (1).$$

Using this definition we modify the control diagram in Figure 1-1 (left) as shown in Figure 1-1 (right). We add a tension unit calculating action tension as reference value for the machine control. Action tension can be discretized for using it as synchronization events within the whole system.

In the literature we find some related concepts. Within the driver-automation system design, Onken [9], for example, uses a 'danger model' that contains a non-directional value named 'time reserve'. It consists of the driver-model based danger estimation and the environment and vehicle limits based danger calculation. This value defines a time slot for a possible action to avoid danger. Under the key-word 'warning toolbox' we find considerations [11] toward integrative action oriented warning strategies in interaction design based on separation of the human-machine interaction timeline toward criticality dependent escalation strategy. These related concepts are highly compatible to the tension approach, although they seem to provide rather *descriptive scalar* metrics, whereat we propose *enabling directed* metrics to emphasize the direction toward certain possible actions to reach the same system state. It is important to note that the tension approach is much more design and solution oriented than related scalar concepts, such as criticality or risk, as it directly considers particular actions, which could be undertaken to resolve the situation. Furthermore, in difference to the known concepts, the tension approach can be seen as an integrative framework for design different kinds of dynamic cognitive systems rather description of singular design methods and singular reference values.

Operationalization

Now, we give a brief overview how the tension approach can be used in the design of cognitive systems, for instance a vehicle collision avoidance system in an approach, brake and evade driving scenario. We show how function parameters of the action tension (1) can be operationalized and how the output $\text{Tension}_{\text{ACTION}}$ can be quantified. To describe action tension, we used first a deductive top down approach from literature and then we confirmed it in an inductive bottom up approach with test persons within a usability study. As mentioned before, action tension is a composed value directed toward a particular action, in our example, avoid collisions by braking or steering. We decided to use the time to collision (TTC) as merged baseline description of the vehicle and the environmental states (S_V, S_E). TTC is defined as "the time required for two vehicles to collide if they continue at their present speed and on the same path" [4]. With it, we had a continuous value describing on a higher level the necessity to act. If TTC is high enough, there is no reason to act in order to change the human-machine state, but if it is approaching zero, the necessity for action and hence for interaction between human and machine is higher.

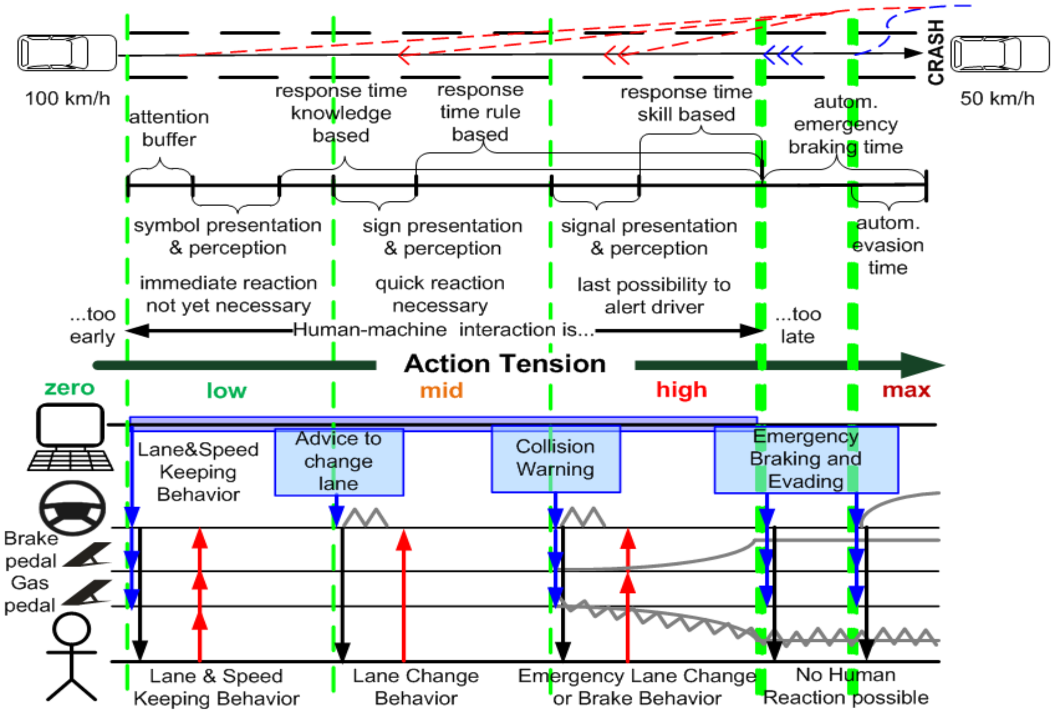

Figure 1-2: Top down operationalization concept of action tension for a vehicle collision avoidance system (top) and a sequence diagram of the interaction design using action tension approach (bottom)

In the **first step**, we used the reciprocal value of TTC to describe the action tension. But consideration of the TTC alone was not enough yet. To model the action tension completely we still had to consider the human and machine states and constraints (S_H, S_M). Also, we had no synchronization events as well.

In the **second step**, we divided the reciprocal TTC progression into five discrete areas (zero, low, mid, high and max) (Figure 1-2 top part). The thresholds between the areas (green dashed lines) should function as a trigger, enabling events in the interaction process and simultaneously initiating automation behavior (e.g. performance of particular maneuvers). Thereby, the aimed point is always the action toward 'area zero' caused by $\text{Tension}_{\text{OPTIMAL}}$. Here, the ratio between performance and arousal of the human is optimal [12] and the machine action as well as the human-machine interaction would be too early. The areas 'low', 'mid' and 'high' were defined with respect to the three levels of control of human action (skill-, rule and knowledge based control action) [10] according to the rising perception and decision times, if we move on this scale toward knowledge-based level of action. The 'max' area was on the critical side of the action tension where no human reaction was possible and the reaching of the aimed 'area zero' was only possible by autonomous machine action.

In the **third step**, we defined the area thresholds by human and machine dependent parameters. On the human side, these were attention buffer (dependent e.g. on limited brake reaction times in attentive and inattentive state [3] and on cognitive involvement caused by the selected level of automation), symbol-, sign- and signal perception times and typical times for action decisions (e.g. the time when most drivers decide for a lane change approaching a slower car [1]). On the machine side the considered parameters were our specific device response times (e.g. of the autonomous emergency brake or evasion) and times to present certain interaction elements.

The top down deduced action tension has been evaluated with test persons in an inductive bottom up process in the **fourth step**. One of the aims was to find out, whether the theoretically identified tension areas also resemble subjectively perceived risk and need for action by an assistance system. Therefore we confronted test persons with situations being prototypical for different action tension areas. The subjects were driving a vehicle on the middle lane of a straight 3-lane highway for a randomized time in different conditions (e.g. without traffic and left lane free and with traffic and left lane closed). Then another vehicle appeared suddenly in front in different distances and TTCs provoking driver reaction in form of a lane changing, braking or evading. The subjects had to react and then they could rate the situation on a semantic differential. The short sample of the results is shown in Figure 1-3. The numbers under the scaled question show the quantity of subject answers. The squares mark the correspondent median values. In general, we observed that the top down deduced tension areas matched to the perception of the subjects.

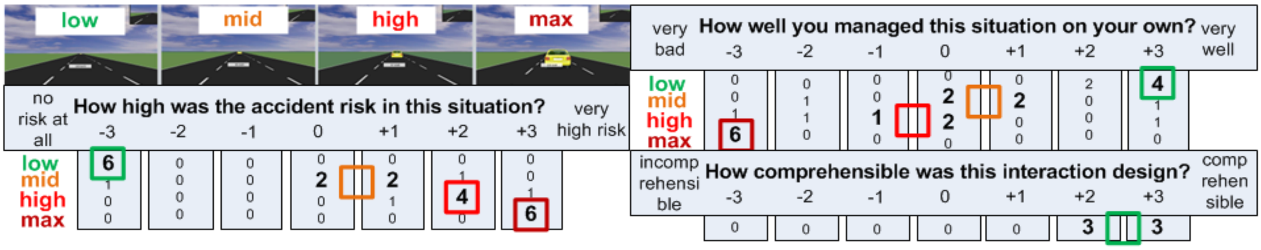

Figure 1-3: Example of the evaluation results for theoretically deducted action tension and evaluation results for interaction design after the tension approach

Using evaluated action tension, we developed in the **fifth step** an interaction design for an integrated approach, brake and evade assistance system. Because the functionality was available in two different levels of automation, we designed different interaction versions with slightly different action tension thresholds for each level of automation. The interaction design for higher assistance is notated in a sequence diagram (Figure 1-2 bottom part). The action tension thresholds were trigger for automation behaviour (e.g. lane & speed keeping, advice to change lane, collision warning, braking or evading) and for haptic interaction on an active steering wheel and pedals. Symbolized interaction, such as double ticks, forces and vibrations, is shown on the life lines of the inceptors.

In the last **sixth step** we evaluated the designed interaction with the test persons. The aim was to evaluate, whether the presented interaction design will be well understood. In the Figure 1-3, a short sample of evaluation results is shown. In general, we observed that the interaction, designed using action tension approach, is well comprehended by the test persons.

Conclusion and Perspective

The tension approach is based on the well-known and accepted scientific concepts. It enables an ontological and holistic kind of system understanding and offers a useful framework for design of comprehensible cognitive systems in a usability improving and system integrating manner. It can be used also on the metaphorical level to enable and implement new system and interaction design ideas. Thereby, the important constraint is the finding of an appropriate manner to operationalize the tensions. However, because of offering a nearness to psychological and technical perspectives, the tension approach allow a domain independent dialog between the professionals from different domains interested in design of cognitive systems, such as human factors experts, engineers, psychologists etc. It is planned to develop the tension approach further toward a useful methodology and a tool-chain for design of cooperative dynamic multi agent systems. The concept of tension within this framework would offer opportunities to derive generic human-machine interaction strategies, which can take place on the future human-machine interfaces in a generic manner. Further, the tension framework can help in deriving user-compatible software and hardware frameworks that would use tensions as reference values within the designed system. Furthermore, because of nearness to physical values, such as tension, it would allow a formal analytical kind of cognitive system design and analysis, for instance, using wave-, field- or graph-theoretical concepts.

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