Designing a Control and Visualization System for Off-Highway Machinery According to the Adaptive Automation Paradigm

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Abstract. This paper aims at describing the requirements of an off-highway human-machine system able to recognize potential risky situations and consequently prevent them. The developed methodology is based on two techniques derived from the field of human factors studies, namely the Hierarchical Task Analysis (HTA) and the Function Allocation (FA), which have been integrated and revised to suit the specific domain of off-highway machinery. The paradigms of adaptive automation and persuasive technology will be followed in the design process. After the off-highway domain analysis a system aiming at improving operator and machine safety is presented. The information system extends the human intelligence monitoring the stability of the machine.

Keywords: Adaptive Automation**,** Collision, Function Allocation, Human-Machine Interaction, Hierarchical Task Analysis, Off-Highway Vehicles, Overun, Rollover, Runover, Safety, Tractors.

1 Introduction

The complexity of on-board equipment for agricultural and off-highway machinery has dramatically grown during the last years. The increased number of functions and devices has led to a substantial modification in working procedures, the contrary of what has been seen in the automotive domain. Cars have been equipped with electronic information- and/or safety-related systems, which have improved the reliability of the vehicles and the user comfort although this has not affected the essential nature of the driving task [1] [2].

On the contrary, the introduction of electronics in agricultural and off-highway machinery has led to a strong centralization of controls inside the vehicle cabin, bringing a significant modification in the way users must manage their working task. This modification has been especially strong in the agricultural field, where most of the tractor functions can be performed from inside the cabin. Moreover, the incoming

D.D. Schmorrow et al. (Eds.): Augmented Cognition, HCII 2009, LNAI 5638, pp. 42–50, 2009.

diffusion of electronics to implements will allow the user to perform settings, calibrations and corrections while inside the tractor. As a consequence, users are facing an increased number of tasks [3]. In spite of its high complexity, the off-highway driving domain has been considered only in a few scientific works concerning human factors and the optimization of the in-vehicle human-machine interaction.

This paper proposes a methodology for selection and subsequent design of tasks that are suitable for partial or total automation within the cabin of an agricultural or off-highway vehicle. The methodology was applied to the domain of agricultural vehicles. The result of the case study led to the development of an on-board application, based on:

- a joystick with haptic force feedback capabilities for a loader of an agricultural machine. The joystick behaved in different ways depending on the scenario around the vehicle.
- a visual display providing relevant vehicle information to the operator. The display alerted the operator of incurring critical conditions, then providing the procedure to keep the system in a safety configuration;
- a set of rules for risk estimation which define the information provision strategies for risk mitigation adopted by the visual display and the joystick.

  This work derives from an Italian regionally funded project called PRO-TRACT (www.pro-tract.it).

2 Approach and Method

The methodology that was developed in this study is based on two techniques derived from the field of human factors studies, namely the Hierarchical Task Analysis (HTA) and the Function Allocation (FA), which have been integrated and revised to suit this specific domain.

The design methodology is divided into three steps. In the first step, the most critical tasks has been established and analyzed through the use of a Hierarchical Task Analysis with the decomposition categories presented by [4]. The second step identified the sub-tasks in the vehicle cabin that would be suitable for partial or total automation and subsequently, different alternatives for automation and relevant information visualization have been generated and evaluated. A method for Function Allocation based on the so-called “York-method” [5] was used here. The appliance of the York-method gave appreciable results in a previous work yet, were a forward collision warning system for the automotive domain was analyzed and designed [6]. Moreover these first two steps have been discussed in [7] and here relevant results will be summarized.

In the last step, the control strategies of the joystick and the strategies to provide information on the visual display have been designed with the aim to keep the operator aware of the most frequent and risky accidents highlighted after the first two phases. These accidents are:

- collision;
- overturn.

A risk-focused design methodology has been followed for the development of the control of the joystick and the information provision strategies of the visual display. This methodology has been defined as a set of rules which describe:

- the vehicle information needed to identify the possible risky condition: e.g. vehicle speed, bucket position;
- how the level of risk associated to both accidents is identified according to the value of these information: e.g., high speed and high bucket position might lead to an overturn accident, coded as an *high level* of risk.
- how the identified risk level is translated into a haptic feedback on the joystick and/or a visual information on the visual display.

Risk-based feedback strategies were designed, that prompt users to perform appropriate control actions, by signaling unsafe handling of machine controls and limiting possible actions to a subset of safe actions. Strategies were implemented by exploiting all available channels: information about the machine's status was presented on the display with two color-coded levels of warning (medium-amber, high-red) and icons identifying the kind of risk currently run by the operator (overturn or collision). Finally, a set of icons suggested how the operator could intervene on the on-board controls (pedals, joystick, steering wheel) in order to get the machine back into full safety conditions.

The approach aimed at extending operator's capabilities of monitoring the stability of the machine, which are currently limited on several respects. On existing machinery, visual monitoring is hindered by poor visibility from inside the cabin, often worsened by dust, dirt and high visual load devoted to the working implement; concurrently, auditory monitoring is mainly hindered by engine and implement noise. The haptic channel is hardly employed for monitoring purposes although largely involved in managing the machine controls (i.e. pedals, knobs, joysticks). Haptic channels has a strong potential for information provision, as operators perform several safety-critical actions (i.e.: controlling implements) by using physical devices: this qualifies them as strong candidates for delivering safety critical information, and for limiting possible actions when such limitation may prevent severe consequences. As a whole, operators' situation awareness is improved, and capability of avoiding risky operations is boosted.

3 The Off Highway Domain

The off-highway domain encompasses farm machinery, construction machinery and special vehicles. The operative context of such vehicles is heterogeneous, therefore operators often accomplish very different tasks. This heterogeneity is due to several aspects:

1. the environment: visibility, climate
2. working area: type of farming and used machinery, road transit
3. equipment: tools layout
4. operator posture: slopes and equipment position

5. telemanipulation: correct action, force, weight perception, consequences on the material integrity
6. precision Farming[1]: activity organisation

In the automotive domain, the driver should lead the vehicle along the road, keeping it safely; the human machine systems complete the driving task and give driver further information. In the off-highway domain instead, the vehicle transition path is not clearly defined and it lacks of precise road signals. Hence the human machine systems are strictly related to the working task, whose are often the exclusive control system.

Recently, some ISO norms (i.e. ISO 11783) have take care of various on-board devices, like virtual terminals, aiming at define physical constraints. These norms are not enough to deal with the off-highway domain complexity because they consider only technological and productive aspects, which represent a little set of the available vehicle functions. It is needed, in the future, the definition of "Off-highway performance science", like the automotive "Driving Science" [8].

Nevertheless there are some user-centred design principles feasible for this domain:

1. **Display**: displays are classified by i) physical features; ii) target user features; iii) task features. The designer aim is to obtain a correct mapping between the display shape and layout and the task to be accomplished, taking care of strength and weakness of human perception, attention, cognition memory, and mental model [9].
2. **Control**: control involves two crucial processes: i) user action selection and performance; ii) feedback loop[2]. Selecting an action is a process influenced by several factors [10] [11] i) decision complexity [12] [13]; ii) events expectation [9]; iv) compatibility between stimulus and response [14], v) trade-off between speed and accuracy; vi) feedback (feedback is dramatically relevant in the joystick design, because in drive-by-wire vehicles the mechanical feedback are missing and they should be emulated by the multifunction joystick).
3. **automation**: automation is generally applied in order to ensure efficiency or to perform dangerous or heavy tasks. For example in the off-highway domain automation is applied in the headline turn function[3].

3.1 On-Board Equipment: Technology Evolution and Safety

The complex growth of on-board equipment for farm tractors and other off-highway machinery has been rather disordered in terms of its consequences for vehicle dashboard and cabin design, into which many complex human-machine interfaces have been introduced [15].

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[1] Precision Farming refers to the in-field variability, By using satellite data to determine soil conditions and plant development, these technologies can lower the production cost by fine-tuning seeding, fertilizer, chemical and water use, and potentially increasing production and lowering costs

[2] The feedback loop allows the user to evaluate whether his/her action obtained the desired effects.

[3] This automated system optimize all the operations needed to set the vehicle to work on a new field section, whenever the last one is finished.

The introduction in the automotive domain of new electronic devices (both informatics and driving assistance systems) that improve the reliability of the vehicle and the user's comfort has not altered the essential nature of the automobile driving task [2] [1], leading to a proliferation of controls in the cabin, which significantly modifies the way users must manage their working task. The use of electronics to manage implements (hitches, loaders, bailers, sprayers, etc.) allows the user to perform settings, calibrations, and corrections while inside the tractor [7]. As a consequence, users must perform an increasing number of tasks [3]. This means that the evolution trend is technological-centred [16]: there is little attention for the consequences innovations have on the operator-vehicle system.

On one hand, automation improves efficiency, on the other hand it dramatically impacts on the human performance. The monitoring of an automated task puts the operator "out of the control loop" [17], favouring his/her deskilling [18], which has crucial consequences in dealing with malfunctions and high risk situations. The deskilling effects would make safety and efficiency worse.

The final aim of a human-centered automation system is the operator and machine safety, putting to use the adaptive automation and the persuasive technologies paradigms [19].

Accident data collected in the last few years (National Ag Safety Database [NASD], 2003) identify the task of moving loads with front-loading tractors as one of the riskiest operations in the field. Furthermore, lifting and moving operations conducted with front loaders are related to rollover and runover events [7].

4 The Riskiest Task: An Overview and a Method of Analysis

The methodology proposed in this article had been implemented during the development of a risk mitigation system for farm tractors as part of the Italian publicly funded project Pro-Tract[4].

During the Pro-Tract project in-depth interviews with experienced drivers were conducted. Drivers said that avoiding a rollover was their most serious safety concern. After the goal was defined, the Hierarchical Task Analysis (HTA) was carried out on the basis of detailed information from interviews and video recordings of seven tractor operators performing this task [7].

The HTA enabled designers to isolate criticalities in tasks carried out by operators inside the cab and, consequently, the automation designs could be targeted for solving very specific problems (e.g., operator overload). The function allocation (FA) provided criteria for assessing the feasibility of viable design alternatives, which facilitated this phase and reduced the potential randomness of the selection process. On the human factors side, this method helped developing detailed descriptions of farmers' activities during fieldwork. Differences between off-highway machinery and the automobile-rooted concept of "driving" (starting from the user's posture inside the

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[4] The partners were Comer Industries S.p.A., a mechatronic research and manufacturing company; Ognibene S.p.A., a hydraulic manufacturer; Walvoil S.p.A., a manufacturer of hydraulic components and joysticks; and the Human Machine Interaction Group at the University of Modena and Reggio Emilia, Italy.

cab) could be highlighted. The apparent similarities between automotive driving and off-highway driving were found to be inaccurate [7].

In next paragraph, the methodology to identify requirements for warning systems will be proposed. The warnings aimed at reducing the risk of rollover and runover accidents while moving loads (e.g., hay, grain, soil) with front-loading tractors.

4.1 Application of Hierarchical Task Analysis and of Function Allocation to the Riskiest Task

The HTA [4] [20] allowed at creating a precise description of the tasks being considered. The analysis consisted of decomposing the tasks into elementary units and organizing them into three hierarchical levels:

1. goals (system state to be achieved),
2. tasks (structured sets of activities required for achieving goals), and
3. subtasks or operations (different sequences of actions that the machine-operator system must perform).

The HTA was applied to one of the most risky work situations for operators of farm tractors, described as follows: "To move a load (e.g., equipment, hay, sand, manure) by means of an implement connected to a farm tractor (operator in cabin with engine on)." Rollovers and pedestrian runovers are two of the most serious and frequent accident types with farm tractors [21] during this activity,

Hence, this task was decomposed in sub-task, in turn decomposed in other subtasks, each of them performed with specific modalities. The template in which the descriptions were included was based on the table proposed by [4]. From the HTA arose one key tasks: an example is "Check physical obstacles", which may put both the operator and pedestrians in imminent danger. The following function analysis (FA) showed that this specific subtask could be partially automated [7]. The tasks structured description derived from the decomposition analysis facilitated the scenario description required for the FA based on the York-method [5], in which different scenarios and trade-offs are used with regard to the allocation of tasks and operations between humans and machines. Task analysis and function allocation both aim to match the human abilities with the system ones, in order to automate the tasks best suited to machines and to maintain as manual the functions best suited to human [22], considering also the benefits with respect to workload, performance, and situation awareness.

Once the basilar functions have been founded, they will be allocated to the machine or to the operator, considering that "a function may be separable from all roles, and technically feasible and cost effective to automate, in which case the function may be totally automated. Alternatively it is possible that the function maps entirely to one of the roles, and is infeasible to automate, in which case the function is totally performed within that role. In most cases however functions fit into neither category. In this situation the function is to be partially automated" [22], [7].

4.2 Constructing Scenarios and Evaluating Candidates for Total Automation

The scenarios were selected in order to focus on critical situations (for example, where workload is likely to be high). Each scenario was described with a subset of functions required in the scenario. In our case, the HTA and decomposition categories defined the most critical subtasks within the areas associated with rollover and runover risks. Hence, we selected the scenarios to include those two risky areas. Each scenario was then described with a subset of functions that were evaluated as candidates for total automation.

Tasks that have low significance for the operator's role are generally proposed as candidates for total automation. For example, for the "work in courtyard" scenario, the operator role is: "the operator is the only person responsible for an efficient (quickness and accuracy) and safe execution of the job. During execution, he/she must prioritize safety over efficiency. Safety is prioritized according to the following hierarchy: safety of vulnerable persons (e.g., pedestrians), own personal safety, safety of objects and items. During the execution of the task, he/she monitors the protection of machines, vehicles, buildings, and the transported load". The function "estimation of the terrain slope" could be totally automated, while "keep the implement height under the critical threshold" is an example of a partially automated task, that is done by the operator with assistance from the vehicle, which provides information about load height or prevents the operator from raising the implement too high for safe operation [7].

When automation would decrease the operator's overall performance it means that these functions should not be fully automated, either because of a substantial cost or because they were considered to be central to the operator's role [7].

4.3 Development of the Risk Mitigation System

The final phase of the work consisted of defining how to translate the inputs from the machine (e.g., terrain slope) or the operator (e.g., a sudden turn) into the in-cab devices. The solution advanced by the PRO-TRACT project team consisted of an on-board computer screen and a haptic joystick. These devices should be set and used in order to allow the operator to safely perform critical task.

When the risk is high, a suggestion is displayed on the screen about how the operator can mitigate the risk. The suggestion is given in descriptive symbols and icons with color coding that corresponds to the risk level and is accompanied by a brief text message. Simultaneously, a beep sounds to draw the operator's attention to the display. For instance, in the case of a high risk for rollover, the display suggestion would most likely be to lower the loader. Simultaneously, a partial automation device would intervene and impede certain joystick movements by generating resistance in the direction that would raise the loader to an unsafe height. On the other hand, if there is less of a risk for rollover, only the visual and auditory warnings would be presented, leaving the joystick functions unaffected.

This solution would require a low R&D cost, given that the main barrier is the calculation of the risk level for rollover or runover. Joysticks for haptic feedback exist on the market; the display design doesn't require significant costs, and the risk parameters would be measured by sensors installed in the vehicle. Several sensor packages that would meet this need have been developed for the automobile market.

4.3.1 The on Board Computer Screen

This display is foreseen in the ISO11783 norm. It inform the operator about the status and the layout of the vehicle equipment. The display a has a data mask and soft keys. The display must allow the operator to build the correct scenario risk evaluation, giving him/her useful hints to mitigate the risk.

4.3.2 The HapticJoystick

The joystick has four motion possibilities (up/down, left/right) and some buttons. It is placed on the operator's right side. The joystick palys a crucial role, because it is the control device of the vehicle equipment and in the most part of dangerous situations it is the decisive intervention tool. Its haptic feedback allows the operator which are the correct or inadequate manoeuvre.

5 Conclusion

Thanks to the hierarchical task analysis and the function allocation methodologies operative scenario were traced and matched with design solutions adequate to the detected risk level (rollover vs pedestrian runover) and to the working context (courtyard vs field). Thanks to the function allocation activity, designers have at disposal a general description of the system behaviour, essential to write the system requirements.

The proposed methodology allowed us at selecting tasks suitable for partial or total automation concerning off-highway vehicle maneuvers.

The resulting on-board application and risk mitigation system, were formed by:

- a haptic joystick with force feedback that behaved in different ways depending on the current scenario.
- a visual display providing crucial vehicle information to the operator.
- a set of rules for risk estimation which define the information provision strategies adopted by the visual display and the joystick.

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