DESIGN OF A TELEOPERATION USER INTERFACE FOR SHARED CONTROL OF HIGHLY AUTOMATED AGRICULTURAL MACHINESS

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ABSTRACT

This paper presents a focused examination of critical performance and design issues for the introduction of highly automated tractors and their user interfaces in agriculture. An industry that as of today mainly uses direct-controlled machines that at least to some extent have partly automated functionalities. Issues include out-of-the-loop unfamiliarity, interface complexity, automation transparency, and changing information modalities in teleoperation scenarios for former cabin-based operated machines. Selected evidence and accompanying concepts and findings from literature are put in context to each issue, informing a systematic design process that utilizes the frameworks of knowledge engineering and ecological interface design. The resulting user interface prototype is built upon the identified requirements in analysis and collected design guidelines, stemming from various research areas. The documentation of the consideration of these in context with additional requirements, such as complexity reduction, information interactivity, and users' existing experiences is meant to provide insights into the often opaque and art-like design space.

Keywords: Design engineering, Knowledge management, User centred design, Design for interfaces

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1 INTRODUCTION

User Interfaces (UIs) in mobile machinery applications are often the product of a technology-centred development rather than a user-centred one that extensively considers operators' capabilities, abilities and requirements. The introduction of highly-automated machines in agriculture will further challenge operators, making human-friendly work conditions by design all the more important. Otherwise, there is the danger of a scenario where the operators' role is reduced to fill the gap of automation capabilities.

Automation operation requires competent operators with the necessary knowledge about automation capabilities and skills to master human-robot cooperation. In the context of highly-automated agricultural machines, such cooperation might occur in teleoperation environments, further challenging operators through a change in information availability and the out-of-the-loop performance problem. This is especially critical, as automation potentially raises the danger of complacent behaviour that can result in a neglect of attentive and thorough supervision and intervention. High trust in automation, insufficient knowledge about automation and difficulties in applying existing competencies in changed environments have been shown to affect such behaviour, indicating the importance of competencies in automation operation. Considering competences in user interface design seems a crucial step towards more effective and reliable human machine interaction. However, as competences are individual and supervising requirements differ among tasks, this raises the question of how adaptable user interfaces can help to consider operators' knowledge, skills and mental models in the transition to automation operation. The core hypothesis is, that improved human-technology fit positively affects the increase of self-efficacy, and decrease the risk of complacency. This paper gives an overview of human-robot interaction performance issues in the context of changed tasks and information environments in shared control teleoperation of highly automated tractors in agriculture and their relation to competence requirements and information availability (Section 1). It reports on an online survey assessing precursors of complacency (section 2), and further discusses suitable UI design approaches to mitigate changes through competency-reflective features in the context of an experimental UI design (Section 3). This research is part of developing the "Feldschwarm" (see figure 1), a highly automated tractor developed in a nationally-funded research and development project currently in test phase and funded by the DFG.

Figure 1: The functional prototype of the Feldschwarm demonstrating automated operation in a tillage mission.

2 TRANSFORMATION OF MACHINE OPERATION IN HIGHLY-AUTOMATED AGRICULTURE

2.1 Transformation of machine operation in highly-automated agriculture

The latest stage of agricultural automation are highly-automated field robots of different sizes and purposes. They demonstrate that such systems may barely rely on human control under normal operation conditions (Pedersen *et al.*, 2018). Nevertheless, the operation of such machines will at least require human involvement for the calibration and adjustment of mission parameters on the field, the confirmation of safety-critical manoeuvers or manual intervention in critical situations (Vasconez

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et al., 2019). Besides technological advancements, there is still uncertainty about the best operation modes for such machines in agriculture. As there is no elaborated concept of an aspired human role underlying the engineering efforts, the standard path of industrial system automation is often to allocate the maximum possible control to the automation side until a critical condition requires the operator to intervene. This strategy may favour multi-machine teleoperation control scenarios with the human out-of-the-loop (OotL) as they can cut required human workforce in machine control, improving the economic balance. Even though this is not a preferred scenario, as it holds many challenges for human performance (Onnasch and Hösterey, 2019), the shortage of skilled workers in this industry may make it necessary to assign one operator to many systems that are distributed to several locations while he or she is involved in other activities of the daily farm business. In this context, the transformation of operation is twofold. First, it is characterized by a shift from manual control to mostly monitoring and planning activities that are interrupted by critical situations where operators have to intervene to ensure system safety and operability or to compensate for automation limitations. Second, it confronts operators used to a cabin-based machine operation with an unfamiliar teleoperation task and an operation environment that has to cover fundamental changes in machine functionalities and behaviour due to its automation.

2.2 Human-performance issues in automation operation

Besides their machine operation and process understanding skills, monitoring several machines and optimizing complex work procedures in teleoperation will bring new tasks and requires new competencies to maintain high work performance in a fundamentally changed and challenging work environment. Supervising highly-automated machines might lead to more inhomogeneous and infrequent workloads, as problems, where operators have to intervene cannot be scheduled (Endsley & Kaber, 1999). Non-continuous machine supervision in shared control teleoperation of several machines may lead to out-of-the-loop performance problems such as impaired situational awareness, increased reaction time and familiarization time and impaired mental model building (Endsley and Kiris, 1995; Parasuraman *et al.*, 2008). In automation operations, situational awareness is also threatened through complacent behaviour, which may result in a neglect of attentive and thorough supervision and intervention (Parasuraman and Manzey, 2010).

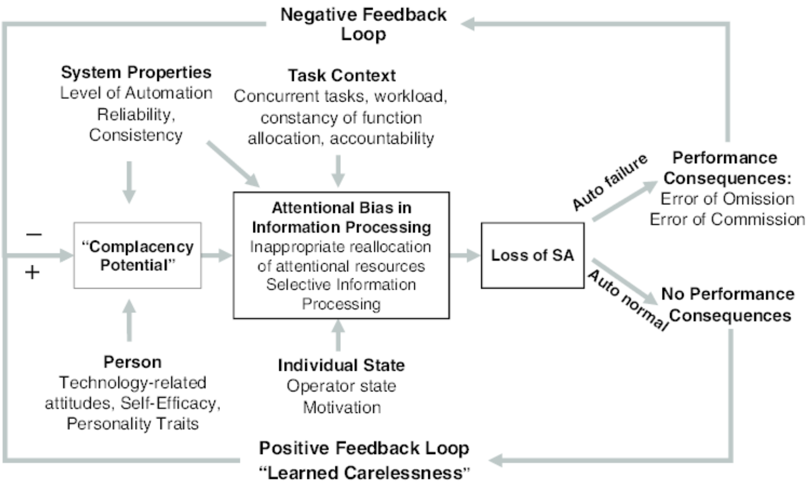

Figure 2: The integrated model of complacency and automation bias from Raja Parasumaran and Dietrich Manzey (Parasuraman and Manzey, 2010).

Figure 2 shows the integrated model of Parasumaran and Manzey that highlights affecting factors of complacency. Some of these factors can be related to user interface design, such as workload, time pressure, complexity, and overall ease of use and some to the operators' competencies, such as self-efficacy towards critical automation supervision or trust. Complacency potentially results in reduced situational awareness and willingness to critically verify the systems acting and their decision-making responsibility, manifesting in decreased process efficiency and effectiveness (Moray, 2003).
Inappropriate trust can be linked to insufficient knowledge of automation capabilities and a lack of experience with automation failures (Hoff and Bashir, 2015).
Sufficient situational awareness in teleoperation is further challenged through the changing information modalities that may result in increased mental workload or even mental model

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incompatibilities. Today's operators are trained to evaluate machine performance based on direct sight, and multimodal perceived machine behaviour (vibrations, sounds, banking of the machine etc.) only complemented by digital data presented in a visual interface. In teleoperation, this rich data has to be transformed, transmitted and understood using mainly the visual channel, bound to state of the art in interaction devices available to machine producers today. This modality transformation at least challenges operators' skills in pattern detection, situational awareness, and workload due to required mental transformations (Wickens, 2002), their ability to assign existing mental models of machine operation and operation environments (Top *et al.*, 2021; Picking *et al.*, 2010) as well as their feeling of immersion or presence (Parasuraman *et al.*, 2008; DeJong *et al.*, 2004; Chen *et al.*, 2011).

Tree major competency-related human performance issues summarize the crucial role of the operators' competencies in 1) impaired situational awareness for out-of-the-loop and teleoperation conditions, 2) poor maintenance of knowledge and skills through decrease and infrequency of active involvement, and 3) impeded applicability of existing competencies due to the changed system and UI functionalities, technology, and behaviour of automated machines, 4) danger of complacency as a result of miscalibrated trust on automation capabilities and 5) the requirements for new competences to meet the new functionalities involved technology and new modes of operation in automated systems. To build up knowledge, facilitating skill acquisition and mental model application becomes crucial for automation operation user interfaces. Regarding the role of human-machine interfaces, there are two views to reduce the severity of these issues:

1. First is to empower operators to master the mentioned situations and requirements.
2. The second is a user interface design that mitigates severity through suitable information presentation and encouraging interaction.

2.3 Assessing risk of complacent behaviour in automation operation among experienced machine operators In agriculture

Complacent behaviour, loss of situational awareness and inappropriate trust in automation ultimately discourage operators to fulfil their role as critical supervisors of automation and to gain understanding during use. Trust in automation, knowledge on automation technology, and self-efficacy towards tasks in automation operation are critical factors that can result in complacent behaviour and neglect of monitoring and intervention activities. Complacency endangers safe operation as operators are meant to be a corrective instance to automation in shared control. It was the aim of this study to assess such competencies and attitudes from experienced operators. An online survey was used to assess subjects (N=8, experienced tractor operators) competencies and ambitions toward automation operation. SosciSurvey is used for the implementation, distribution, and data collection. General willingness to engage and General willingness to supervene are assessed via four 6-point Likert scale items (three positive and three negative statements on whether one will intervene or not) and two sliders which subjects could use to express their expectations regarding the automation accuracy in a situation analysis and action selection in general. Task-specific self-efficacy is assessed using numerical scales representing operators' confidence in specific tasks. Banduras' guide on constructing self-efficacy scales (Bandura, 2006) was used to build four scales for four different classes of tasks each. Three address specific tasks in automation operation and use of advanced electronic technology. In addition, self-efficacy regarding conventional machine operation tasks and general self-efficacy (GSE Scale, (Schwarzer, R., & Jerusalem, M., 2002)) are assessed as baselines. Further, knowledge of automation technology in agriculture is assessed via a self-designed multi-choice knowledge test. Knowledge of conventional machine technologies was similarly assessed for comparison. Trust in automation was assessed using the trust and propensity to trust scales introduced by Merritt (Merritt, 2011).

Results revealed high ratings for trust in automation and medium ratings for the expectations of required supervising, which could increase the likeliness of complacent behaviour. Nevertheless, subjects also reported a high willingness to engage, which could be evidence of a solid sense of duty. Data also shows low scores in automation knowledge compared to high scores in conventional operation knowledge and medium self-efficacy ratings towards automation operation tasks compared to high self-efficacy ratings for conventional machine operation tasks. Affinity for technology interaction rating is in medium to high range. Results regarding the danger of complacency are mixed. High trust and limited knowledge of automation support complacent behaviour. High willingness to engage and high willingness to supervise might reduce the risk of complacency. However, whether such behaviour will show in actual automation operation cannot be answered as it is affected by many

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more factors. One can hypothesize that missing knowledge of automation technology and unfamiliarity with automation operation situations have adverse effects on automation operation-related self-efficacy and the actual application of competencies in such situations.

Results shows, that operators do show potential for complacency and situation assessment problems. In an industry where these two criteria are the central business drivers and are meant to be maxed out during operation, even mild degradations of these can be show-stoppers. The same is for potentially required excessive training efforts to enable operators to use such systems, as the financial profit margin of operating such systems is still very small. The introduction of such a system could fail, if these issues aren't solved effectively enough. This poses the question of how user interface design can encounter the complacent behaviour and the maintenance and building of competences.

3 CONSIDERING COMPETENCIES IN USER INTERFACE DESIGN

3.1 Conducive design of user interfaces

Despite increasing levels of machine autonomy, future operators still depend on a holistic domain understanding to successfully supervise highly-automated machines and control production processes (Vasconez *et al.*, 2019; Arnold *et al.*, 2016). Systems that consider the operators' competencies in their design and functionality may enable improved performance, reliability and safety. Conducive Design advances the widely applied human-centred design approach by considering operators' competencies and mental states in two ways. First, through a system design that meets human capabilities based on an informed development strategy that regards such characteristics. And second, in the awareness of the system's short, mid, and long-term effects on the users. On a more advanced level, this concept also envisions systems capable of detecting the operators' states to adapt their appearance and information load accordingly in real-time (Kessler *et al.*, 2022). Related research in interaction design, human factors, and cognitive sciences on automation operation highlights the interplay between operators' competencies and states, contextual conditions, information availability, presentation and interaction. HMIs, as filters and converters of system information and controls, play a vital role in mitigating imperfect system design in the context of individual user capabilities (Muslim and Itoh, 2019; Nuamah and Seong, 2017 - 2017). Careful selection and visualization of information and interaction have been beneficial in improving information acquisition (Panteli *et al.*, 2013), information analysis (Kondo and Collins, 2014; Plaisant *et al.*, 2002; Doi, 2019), decision-making (Zohrevandi *et al.*, 2022), action selection, and action implementation (Navarro *et al.*, 2018), mental model building (Doi, 2019; Rapp, 2007) and to avoid downturns in process efficiency, operators' competences or even rejection of technology in many experiments.

3.2 Theoretical approaches to a conducive user interface and forms of interaction

A vast body of knowledge, empirical findings and design recommendations in the literature consider the operation of highly-automated machinery. This section discusses their relevance in maintaining and expanding operators' knowledge and skills.

To tackle the Out OotL performance problem, Wickens et al. discussed the role of automation transparency, emphasizing intelligible systems through user interface design (Wickens, 2018). Research on how user interface design and interaction can effectively improve knowledge of automation functionality led to the concept of intelligible interfaces (Lim and Dey, 2009). Intelligible interfaces provide additional information that helps operators to gain knowledge of how a system works and respectively support the building of correct mental models of the system. UI designs and visualizations aiming to prevent critical loss of situational awareness were presented, evaluated, and discussed by (Ackerman *et al.*, 2017), (Holsopple *et al.*, 2010), and (Panteli *et al.*, 2013) finding positive effects of the additional information on automation activities provided to the operators. All of these user interface designs picked up some of Ensley's situational awareness-oriented design principles (Endsley *et al.*, 2003), for example, the mapping of system functions to the goals of the user, the spatial grouping of data and alarms around critical decisions, again the provision of system transparency as well as an overview level focusing critical conditions.

The change in familiarized system communication challenges existing mental models and observation strategies, as information occurs in different forms and groups. As certain situations are visualized in other ways, they express themselves in new patterns of information. Increased sensitivity to these patterns has to be learned by the operators. However, the user interfaces design might help the

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operator by doing so, for example, by utilizing sensor fusion and visualization (Meier *et al;* Fong, T., Thorpe, C., & Baur, C, 2001; Reina *et al.*, 2016), map-based user interfaces (Paelke, V., Nebe, K., Geiger, C., Klompmaker, F., & Fischer, H, 2012; Averjanova *et al.*, 2008; Francesco Ricci *et al;* Masoodian and Luz, 06062022; Opiyo *et al.*, 2021), mimicking animations (Sandouka, 2019; Tversky *et al.*, 2002) and multimodal interfaces (Sarter, 2002, 2006; Robertson *et al.*, 2009) with the aim to close the gap between real world experience and abstract visual information.

However, intelligibility through additional information may increase interface complexity and, therefore, also impede situation assessment performance. Also, transparency requirements and competencies arguably differ regarding individual operators, tasks, systems and level of experience with highly-automated machines. Therefore, a conducive user interface that considers the operators' competencies must be adaptive or adaptable to some extent. We want to understand how adaptable user interfaces can help consider the operators' knowledge, skills and mental models in automation operations to improve human-technology fit, increase self-efficacy, and decrease the risk of complacency.

Adaptive user interfaces can change their content, look, and behaviour regarding different contexts of use, such as operators' competency levels and related knowledge and skill-based expectations or mental models (Kühme, 1993; Kantorowitz and Sudarsky, 1989). Evidence supporting the effectivity of intelligibility of automation user interfaces has already led to design guidelines and evidence regarding the effects of levels of transparency on operational performance (Pokam *et al.*, 2019; Debernard *et al.*, 2016). In contrast, reliable context awareness and interface adaptivity have yet to reach industrial applications as it is very challenging to predict users' requirements and expectations with necessary accuracy and reliability. Furthermore, adaptable user interfaces have the potential to support the transition to higher levels of automation as they can facilitate direct human involvement. This strategy could be used to both empower operators and collect expertise and data for future automation. Mental model-focused adaptability features of user interfaces could be a promising approach in enabling operators to master the transformation in system operation through automation. However, additional control activities, increased workload, or interface complexity potentially hinder effectivity. Further, the effective design of adaptable interaction that provides actual performance improvements requires research on mental model-based adaptation requirements, suitable forms of competency-based adaptability, and the actual use of such features in real automation operation situations.

Other than adaptive interfaces, in adaptable user interfaces, the operator is responsible for the composition of the user interface. However, that operators can express their requirements directly comes with the cost of extra configuration efforts, which may result in increased workload, time on task, and distraction. Case studies on adaptive and adaptable user interfaces suggest that customization is not very useful in dynamic situations but does not necessarily result in higher workload and is generally preferred (Stuerzlinger *et al.*, 2006).

3.3 Hypothesis and experimental interface and setup

Based on the theoretical findings, this section discusses opportunities for competency-related adaptability of user interfaces for machine supervision and reflect insights from several user observations in agriculture. Figure 3 shows an exemplary user interface that realizes such adaptability. Even though considering competencies in UI design promise beneficial effects on operation performance, additional information needed in intelligible interfaces and additional interaction needed in adaptable interfaces may also result in hindering effects regarding complexity and workload, putting their acceptance at risk. User interface features must be considered to meet operators' requirements and balance operators' familiarisation efforts with tangible improvements in performance or comfort. The following information visualisation and interaction approaches conceptualise interface adaptability on different levels. They consider adaptable availability and form of information, adaptable form of information presentation and present different forms of interactions for adaptability.

Adapting the information complexity by means of amount of displayed machine parameters could be beneficial to decrease visual clutter and highlight important information and increase situation assessment performance. This could for example be realized through an expandable information cluster (A) that allows the operator to increase information depth selectively. These clusters show high-level performance parameters in the default view and provide related machine parameters through a touch gesture on the cluster. Grouping machine parameters that are causally related could facilitate machine state analysis, cause diagnostic procedures and knowledge building. However, observations have shown that operators strictly rely on different familiar parameters in their workflows. Permanently locking certain information to the default view (B) is a necessary feature not to harm operators' workflows. (reducing complexity, providing knowledge on related parameters)

The experimental interface further provides different forms of information presentation (C), including numerical, basic and advanced graphical representations for each piece of information. Operators can assign different pre-sets of visualisation to each piece of information, selecting the one that best fits their current requirements in machine supervision tasks. Switching of visualisation forms can also be achieved through touch or swipe gestures. In conventional machine terminals, some parameters are mapped to a vehicle silhouette to facilitate orientation, utilising knowledge and mental models about the machine's components. An animated and more abstract version could be beneficial to further visualise the multi-dimensional machine state through animation (movement, vibration, rotation and linear acceleration in the x and y axis), which mimics machine behaviour as experienced in reality in a cabin-based control environment. This could help ease the application of existing mental models of operators in teleoperation. In the experimental UI, this is combined with a map-based visualisation that shows the machine's behaviour, performance, and position, including target states and deviations, as well as the programmed route and implement control (D). Observations show that especially experienced operators are reluctant to new forms and structures of information presented as they sceptically approach the required familiarisation efforts. In this case, the adaptability of the presentation form enables operators to experiment and explore its benefits when they feel comfortable doing so. In out-of-the-loop scenarios, operators may rely on temporal data for specific machine parameters that show their course over the last minutes. User interfaces utilise diagrams in other production domains, such as stationary machines. However, presenting diagrams for all parameters will not fit display spaces and harm clarity. In using adaptability, this information can be selected and combined as the operator needs them. The experimental interface uses a separate area where temporal data of several machine parameters can be blended (E). As described above, automation activities are often hidden, and their consequences on machine behaviour can easily be mixed up with environment-induced machine behaviour. Therefore, to enable operators to comprehend these activities, the user interface shows the different automation systems and their activities in dynamic causal structure diagrams (F). These show the involved sensor data, the applied rules and the resulting interventions in machine control, and the time left until the intervention is executed. Furthermore, machine parameters directly controlled by the machine control automation are highlighted while automatically adjusted.

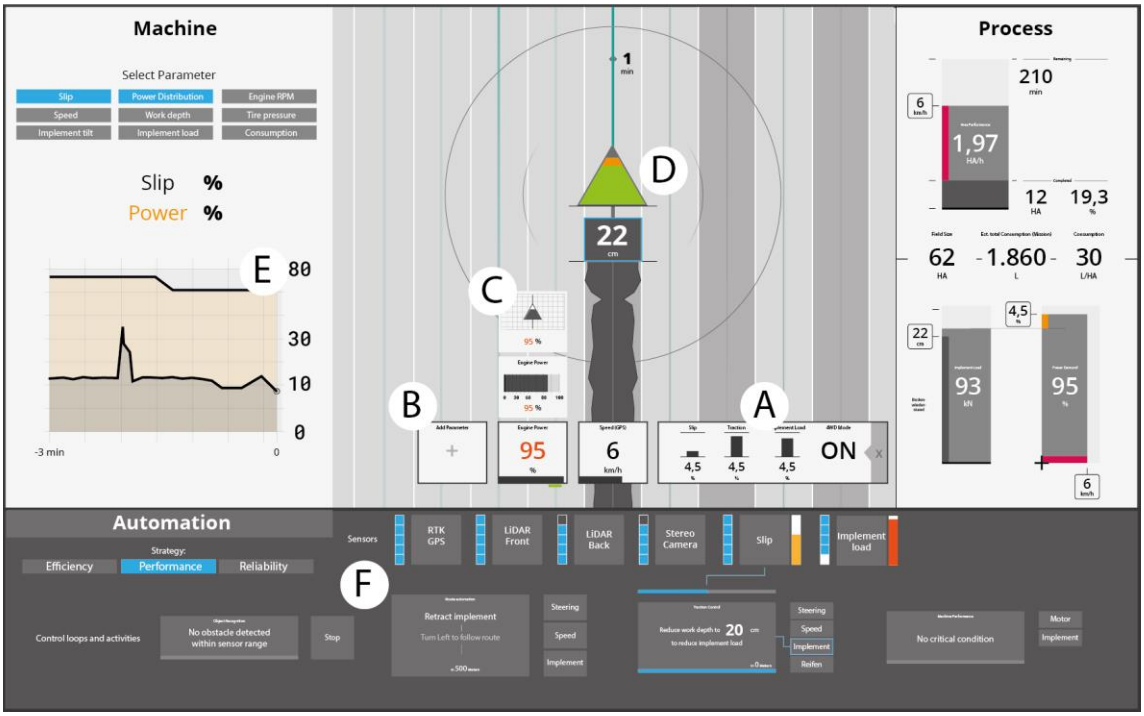

Figure 3. Example screen of the dashboard view of the experimental user interface

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4 DISCUSSION AND FURTHER RESEARCH

Whether the implementation of these approaches facilitates a superior performance regarding the underlying issues of impaired situational awareness, changed information modalities and complexity, insufficient mental models and hindering attitudes remains to be researched in experimental studies comparing each interface condition separately against a conventional setup. The experimental user interface is an interactive prototype that can derivate experimental setups that isolate certain adaptivity functions. For example, how operators use adaptable interfaces to meet their requirements and how the necessary interactions impair performance have to be examined in experimental studies. To further improve overcoming the issue of changed information modalities, it seems promising to transfer the presented design features to an augmented reality display utilizing live camera streams or to use sonification - the mapping of information on acoustic signals - that mimics real-world machine sounds as they are also an intensively used modality in conventional cabin-based machine operation.

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