# Unmanned Aerial Vehicle Control Interface Design and Cognitive Workload: A Constrained Review and Research Framework

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*Abstract*— **Unprincipled design of unmanned aerial vehicle (UAV) control interfaces can increase operator cognitive workload and degrade performance. It is important to identify optimal interface design features that can serve to prevent cognitive overload under demanding task scenarios and environmental conditions. The present research summarized literature on critical issues in supervisory control interface design, current UAV interface design approaches and existing evaluation methods. A research framework was also proposed for a project to systematically and quantitatively relate UAV control interface features to cognitive workload outcomes. The framework also supports development an effective and efficient interface evaluation tool to predict cognitive workload based on specific design features.**

## I. INTRODUCTION

Unmanned aerial vehicles (UAV) have experienced rapid growth in use in recent years. Both military and commercial systems have been applied, for organizational and personal uses and are prevalent and expected to continue to grow in application [1]. Consequently, from safety and performance perspectives, it is important that unmanned aircraft are effectively and efficiently controlled through well-designed interfaces.

UAV system designs have multiple attributes including: autonomy (e.g., fixed level, adaptive automation), control modes (e.g., manual control, supervisory control), and control interfaces, such as visual presentation of information. The goal of most interface attributes is to maximize information transfer, minimize cognitive and sensorimotor workload, as well as minimize training time for users [2].

The concept and specification of UAV attributes in the systems design phase ultimately affects interface usability. For example, lower levels of control provide more immediate operator access to aircraft attitude but require greater integration of system information by a pilot in order to achieve a particular flight goal; whereas, higher levels of control require less integration but do not allow immediate access to lower-level control functions [3]. Related to this example, it has been found that "performance-level" control joysticks, commanding bank angle and vertical speed, are more effective for performance than direct control of aircraft surfaces. On this basis, some research has concluded that there is no need to allow for control inputs below the performance-level in UAV operations [3]. Beyond this finding, mission execution time has been found to decrease when control interfaces provide the capability for pilots to delegate task functions to automation and allow for flexible manual control [4].

Having made these observations, most studies in the current literature focus on increasing the level of UAV automation, overlooking potential benefits of low-level visual information presentation on pilot information processing and system understanding [5]. That is, there may be differences in the functional utility of interfaces depending on the level of automation. Opposite to this, the manner in which an interface delivers information to operators through visual or auditory channels influences overall usability of the control interface regardless of the level of automation and/or control mode. Therefore, the importance of the operator interface does not diminish as the level of autonomy increases [2].

Among different control modes, supervisory control interfaces are designed for high-level command generation, monitoring, and diagnosis [2]. At higher levels of unmanned vehicle automation, physical control vehicle is no longer the primary task, and the operator role shifts from teleoperation to telerobot control or mission supervision tasks [6]. Supervisory control interfaces should therefore focus on supporting the operator's role as information analyst and decision-maker [6]. Related to this, there are many design challenges for supervisory control interfaces including display layout, facilitating sharing/trading of control, and managing human-machine interaction [2]. For example, supervisory control interfaces must provide mechanisms for the operator and the machine to exchange information at different levels of detail or abstraction [2].

Some studies have identified UAV interface design features that are the subject of operator complaints including: inappropriate color combinations (i.e., red graphics on blue background), non-intuitive symbology, inaccurate displays, and confusing abbreviations [7]. Furthermore, operator performance can be negatively impacted by poor interface design under demanding task scenarios due to high workload [8]. In contrast, good design features, such as appropriate placement of fonts and text, appropriate use of shapes, symbols and interaction styles (i.e., stick-and-rudder vs. point-and-click) [7], and appropriate arrangement of information [6], serve to minimize operator mental fatigue, reduce operator response time [7], and facilitate operator information

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processing [6]. Therefore, well-designed interfaces should seek to minimize cognitive workload under a given task scenario.

The present research proposes a methodological framework to relate UAV supervisory control interface features to cognitive workload and to provide a basis for developing an effective and efficient evaluation tool to predict cognitive workload based on UAV interface design. This framework is expected to help designers or human factors researchers who want to perform deeper and more thorough evaluations of UAV operator workload by using systematic and quantitative techniques. This article summarizes our literature review on UAV supervisory control interfaces, current design approaches and existing evaluation techniques, followed by a detailed description of our proposed framework and strategy of future research.

## II. Issues with UAV Supervisory Control Interfaces

### A. Accident Data

Based on an analysis of military unmanned aircraft accident data, Williams [9] found that, depending on the platform, 21% to 67% of total UAV accidents were attributed to human factors issues. Williams categorized the human factors issues as problems with alerts/alarms, display design, procedural error, skill-based error, or other [9]. Many of the identified human factors-related accidents could be explained through analysis of the user interface and identification of potential design problem areas [9]. Williams pointed out that, if such analyses were carried out early enough in the design process of the supervisory control interface, then solutions could be implemented, possibly preventing the loss of systems [9]. Without such design changes, human error due to inaccurate perception and manipulation of a vehicle could lead to loss scenarios, such as the complete destruction of a vehicle.

### B. Human Factors Issues

In UAV supervisory control, operators are required to track both basic status information (i.e., altitude, heading, speed) as well as displayed data gathered by sensors on-board the unmanned vehicle system (UVS) [10]. If an operator doesn't know how to perform these functions by using an interface, the level of achievable input and the efficiency of interface controls is of little relevance to overall system performance [11]. Chen et al. [12] summarized operator performance issues in four categories, including: multi-tasking performance, trust in automation, situation awareness, and operator workload. Provided operators have adequate knowledge of the system, these issues can be addressed, in part, through interface design. Related to this, Chen et al. also discussed some typical interface design issues in supervisory control of unmanned vehicles. For example, while many commercially available UVSs are operated with a single screen display, more complex platforms might offer multiple displays to track system critical information, mission specific sensors, or payload sensor output, depending on the use of the system. Without proper design considerations, multiple displays can result in the need for operators to rapidly switch attention between displays, potentially leading to perceptual registration errors and change blindness [12]. As another example, the type of camera viewpoints presented in vehicle or payload control displays can vary, including egocentric and exocentric. In vehicle-navigation tasks, egocentric camera views can challenge operators with a "soda-straw" presentation of UVS surroundings, potentially compromising operator awareness of global information, such as a changing operation space [12]. Alternatively, exocentric views common to UAVs can cause a "loss of immediacy and true ground view", meaning the operator may have a harder time distinguishing travel distances of ground objects and their true sizes, as opposed to their perceived relative size [12]. Similarly, alternative camera styles (e.g., infrared) can confuse operator identification of environmental objects, if simple color schemes or presentation methods are not available [10]. These are examples of how supervisory control interface design issues can meditate trained UVS operator performance.

Another UVS design issue that can influence the effectiveness of control interfaces and lead to operator performance problems is lag in system responsiveness to control actions. Several UVS platforms follow a "turn-taking" control paradigm (e.g. NASA's Curiosity Rover and long distance UAVs) in which operator actions are followed by automated systems execution in a serial manner. This control approach can introduce extra time between operator input and UVS execution. System sensors can then return this lag so the operator is not receiving real-time data or information, leading to frustration with the system and errors in future decision making [11], [12]. Operators may use the delayed feedback to make decisions that are inappropriate for the immediate situation. In extreme cases, operators may even need to enter batch commands, which could compound control errors.

The human factors issues identified above are the most common issues identified in the current UAV supervisory control interface design literature. They represent target issues for enhanced UAV design approaches.

## III. Current Design Approaches

There are several approaches that researchers and manufacturers have taken to designing UAV interfaces. Two of the most prevalent approaches are ecological interface design (EID) and human-centered design (HCD). Both approaches seek to minimize cognitive workload by capitalizing on design standards and some studies have demonstrated effectiveness [13]. EID emphasizes organizing equipment and functions to match them to user performance modes and mental models. Interfaces developed based on an EID approach are intended to support user mental models and dynamic adaptation to task demands guided by situational variables and user subjective preferences [14]. The approach not only considers the individual components of a system, and the human information-processing demands, but the larger context or the ecology of the work [14].

Existing HCD guidelines primarily address low-level physical control or generic human–computer or human–system interaction (HCI and HSI) needs, rather than higher-level operator cognitive issues. When guidance is given beyond low-level HSI and HCI, recommendations are typically conceptual and there is no consensus regarding implementation in an actual design process [15].

Piccini [15] developed a methodological framework to support designers of control systems and human–machine interfaces, by organizing modern theories of supervisory/cognitive control and HCD principles. Piccini's framework [15] allows for formalization of all the functional, structural/dynamic and operational aspects of supervision and control systems. Based on this framework, integrated HCD guidelines were developed to address system management and organizational issues, contextual issues, automation and function allocation issues, and human machine interaction issues.

Both of the design approaches identified here have advantages and disadvantages for UVS interface development. Although the EID approach can be quite effective for linking user goals and information processing needs to specific functional system features, application of the methodology is laborious and can benefit substantially from a legacy system as a starting point for enhanced designs. The HCD framework approach is less effective in terms of addressing overarching user cognitive needs but is highly useful for constraining new conceptual design and translating design concepts to prototypes.

## IV. Current Interface Evaluation Methods

There are currently several tools and methodologies presented in the literature that can be used for evaluation of interface designs for supporting human performance. These tools range from subjective measures of cognitive workload to interface design checklists (or interface scoring systems) quantifying the degree of design adherence to human factors standards. Some of the established tools have been adapted to various domains in order to account for specific interface user information processing needs as well as workload demands under different operational conditions.

For example, the Federal Aviation Administration (FAA) has used the Cooper-Harper subjective workload rating scale for assessing aircraft pilot cognitive demands in order to gauge whether an interface design is effective from a performance perspective [6]. The Cooper-Harper scale gives an ordinal rating; grading interfaces based on how much additional cognitive demand a design places on pilots. Cummings et al. [6] adapted the Modified Cooper-Harper scale to the UAV domain (MCH-UVD). The tool mimics the FAA standard and applies UAV domain specific constraints and issues to the same scale. The MCH-UVD addresses higher-level UAV operator cognitive demands instead of lower-level control skill requirements through a process of diagnosing display issues. Cummings et al. correlated pilot workload ratings using the MCH-UVD with actual demands placed on pilots while executing search and rescue tasks. Results revealed 86% of participants to find the MCH-UVD helpful in identifying UAV display improvements, and 15% suggested using checklists to grade displays; that is, augment the MCH-UVD scale.

Within the industrial processing realm, Ponsa et al. [16] observed that the complexity of process supervision demands an integration of human factors design approaches and HCI evaluation for effective interface development. With the objective of improving the efficiency of HCI in industrial processes through usability and cognitive ergonomics, the researchers reviewed a number of human factors and industrial guidelines and captured the breadth and depth of requirements and recommendations for interface design. They then developed a strategy for evaluation of HCI effectiveness in supervisory tasks in industrial control rooms based on the collection of guidelines. Ponsa et al. [16] identified 10 high-level indicators/features of effective design including: architecture, distribution, navigation, color, text font, status of devices, process values, graphs and tables, data-entry commands, and finally alarms. Each design indicator was further characterized in terms of sub-indicators or specific design guidelines for each feature. Ponsa et al. [16] also developed an interface scoring system for each indicator, based on the degree of supervisory interface design conformance with the collection of sub-indicators. An evaluation index can be calculated for each indicator using criteria defined by Ponsa et al. [16]. Beyond this, the authors proposed an aggregate indicator score, or global interface evaluation. This approach yielded a global Ergonomic Guideline for Supervisory Control Interface Design (GEDIS) evaluation. Although the GEDIS was originally intended for the industrial process environment, the tool provides a conceptual foundation for customized interface analysis approaches that can be applied across other domains.

Lorite et al. [17] extended the GEDIS framework to the UAV domain in an attempt to create an objective and quantitative interface scoring methodology based on established human factors and domain specific design guidelines. When formulating the GEDIS-UAV, the researchers retained the same indicators and scoring scheme as assembled for the original GEDIS but revised sub-indicators to account for domain specific features. On the basis of Ponsa et al. [16] work, Lorite et al. proposed that interface design conformance with sub-indicators be rated on a scale from 0 ("inappropriate) to 5 ("appropriate") and that the global (or aggregate) evaluation index have the same range. They also proposed that an index value of 4 or more points be considered as a criterion for "positive" design. Whereas, designs with global scores of 3 or less should be considered "unacceptable". The individual sub-indicators receiving the lowest ratings are identified as targets for design improvements, which is a procedure similar to heuristic evaluation as part of usability analysis.

Unfortunately, the GEDIS-UAV provided limited justification for usage of the indicators adopted from the original GEDIS as well as sub-indicators collected from various guidelines. Ponsa et al. [16] and Lorite et al. [17] did not provide an overarching framework, such as a domain specific cognitive task analysis or collection of usability principles as bases for functional and usability indicator identification. This limitation makes it difficult to assume completeness of the set of design indicators as a basis for comprehensive interface evaluation. Moreover, the sub-indicators identified by both research teams were not supported by detailed references to the literature, making them appear subjective or arbitrary in nature. In order to ensure the accuracy and validity of interface analysis using GEDIS-UAV, all design indicators need to be characterized in terms of specific, empirically supported design guidelines. These issues need to be addressed in future research to further enhance the GEDIS methodology.

Usability testing is a broadly defined methodology used to assess whether an interface presents necessary functional features and whether the features are easy to use [18]. There are many different methods for testing usability, but most measure learnability, efficiency, memorability, errors, and satisfaction in order to iteratively improve an interface [19]. Kaber et al. [20] conducted a usability inspection of commercial aircraft flight management systems with expert pilots. The pilots were asked to assess a multifunction control display unit interface in terms of usability principles and identified violations of learnability, flexibility, and robustness. These violations were translated to design recommendations, including use of global metaphors and maintaining consistency among interface screens in order to minimize pilot working memory requirements and workload and to increase available attentional resources. Related to this study, Cavett et al. [21] videotaped UAV users in performing simulated search and rescue tasks while using two different UAV controls interfaces. The users were asked to provide verbal protocols (think aloud) during the recording of experimental sessions. In addition, user performance was measured in terms of training time, task completion time, number of errors, and satisfaction level evaluated during a debriefing survey. Cavett et al. [21] said that all these results could be integrated together to develop a function quantifying interface utility for human performance (UHP). They also proposed that the utility function could be applied to enhance UAV interface design from a pilot perspective, including recommendations on specific interface features through multiple iterations of the functional analysis. The human performance utility function (UHP) they developed was a simple linear equation with weighting factors applied to various user outcomes measures, based on estimated relevance to the UAV interface design:

$$UHP = .5UA + .3UPT + .1T + .1US, \qquad (1)$$

where UA = User Accuracy; UPT = User Processing Time; T = Training time; and US = User Satisfaction.

Cognitive task analysis approaches can also provide explicit guidance on redesigning existing systems in many domains [22]. Kaber et al. [22] paired Goal-directed task analysis (GDTA) with abstraction hierarchy (AH) modeling to characterize the knowledge structure of an expert group of users in research on supervisory control interface design for high-throughput biological screening processes. Five subject-matter experts provided commentary on shortcomings and advantages of an existing control interface and then ranked interfaces from 1 (“low”) to 5 (“high”) in terms of ten characteristics (complexity, consistency, learnability, ease of use, etc.). The researchers formulated guidelines from the GDTA and AH results along with the results of the usability heuristic analysis to create a new interface design. This new interface was tested and achieved higher scoring, according to experts, due to its intuitiveness and improved interactivity.

In general, it is important to note that across the range of interface analysis methods described above, experts provide critical insight for system designers. In cognitive workload analysis, expert pilots are needed for ratings of demands imposed by interface designs under specific operating scenarios. In application of the GEDIS methodology, there is a need for human factors design and domain experts to assess the degree of conformance of any interface design with desirable features and associated specifications. In usability evaluations, subject matter experts are needed to assess the degree of violation of usability principles by existing interface designs or new design concepts. The experience of expert operators provides a basis for making recommendations to improve interface design characteristics in terms of system control usability and efficiency.

Any new methods of interface evaluation for UAV supervisory control will likely need to incorporate expert judgments at some stage of the evaluation process. Therefore, there is a need for developing highly structured and systematic approaches for interface evaluation that are rooted in accepted human factors and HCI design principles.

## V. Proposed Research Framework

### A. *Research Motivation*

By examining existing interface evaluation methods, we found that many techniques are heavily dependent on subjective opinions of evaluators. For example, the MCH-UVD requires an analyst to assess the degree of difficulty of pilot-vehicle display interaction and to generate a quantitative rating. Of course, varying perceptions of the level of difficulty could lead to different ratings. Regarding application of the GEDIS-UAV methodology, unless specific criteria are identified for analyst ratings of the degree of interface design conformance with sub-indicators (e.g., absence of small fonts), the evaluation process can be highly vulnerable to personal preferences and rater emotional states. Other methods, including usability inspection and cognitive task analysis, allow for more reliable assessments to be made of interface design from the perspectives of ease of use and functional utility; however, they can be time-consuming, labor-intensive and costly. More importantly, the majority of existing methods only focuses on particular aspects of interface design and do not provide the capability to predict operator cognitive workload outcomes.

In addition to the desire for objectivity and efficiency in interface evaluation methods, there is a need to ensure any technique is comprehensive in nature. From a design effectiveness standpoint, it is beneficial if an evaluation method can take into account multiple aspects of an interface, including usability features, functional capabilities, operator information processing quality, and resulting cognitive workload. With such a technique, a comprehensive list of design deficiencies can be revealed and used as a basis for making interface improvements.

### B. *Description of Framework*

Considering the primary objective of determining how UAV supervisory control interface features influence user cognitive workload, and the secondary need of providing a basis for developing an effective and efficient interface evaluation tool to predict interface cognitive workload, we propose an integrated research UAV interface design and workload analysis framework (see Figure 1). The framework consists of six sections, representing the scope of our current research program and the flow of work.

Section 1 involves identifying existing interface design approaches, like EID and HCD, along with specification of anticipated levels of automation and control modes, to be accessed and employed through UAV interfaces. All of

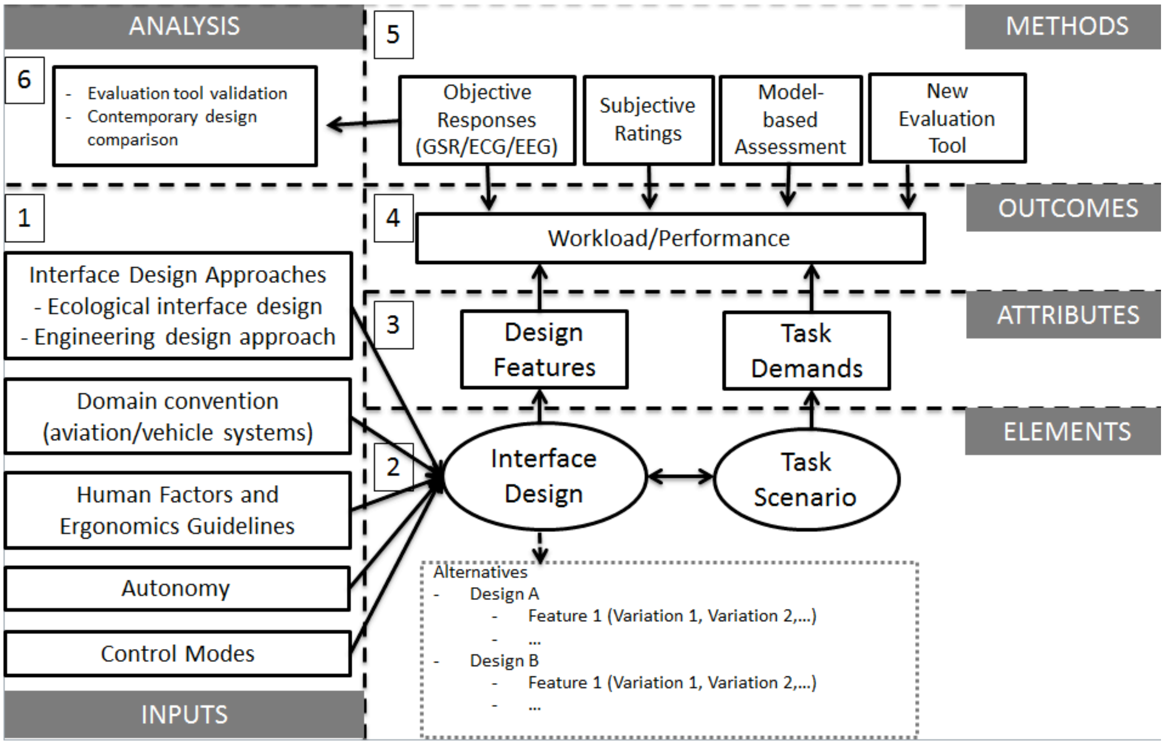


Figure 1. Research Framework

these elements serve as inputs to any UAV supervisory control interface definition.

Section 2 identifies the major elements of use cases. There can be variations on the UAV interface design as well as different task scenarios. In particular, the perceptual and cognitive requirements of operator performance as well as task cycle time serve to dictate specific design features as well as task demands.

Section 3 identifies interface and task demand attributes that ultimately dictate possible operator workload and performance outcomes, in the context of the use case. Each interface design is comprised of a set of design features. Each task scenario can generate different types of demand (physical, cognitive, temporal, etc.) and levels (underload, moderate, overload). The unique combination of design features, plus task demands, drives overall operator load and effectiveness in UAV control.

Section 4 is a critical part of the framework as it involves identification of workload and performance outcomes of interest and emphasizes the utility of interface analysis. For example, workload levels can be expressed in terms of task requirements, such as operation counts or durations (objective quantities), or cognitive demands, like working memory chunk counts or resource channel usage (subjective quantities). Furthermore, performance outcomes, such as speed and accuracy, or visual behaviors, like eye-gaze patterns, can be critical for validation of workload outcomes. In general, selection of the type of workload outcome dictates the objectivity of any prediction model to be developed based on the framework.

Section 5 identifies a number of different types of methods that can be used to measure operator cognitive workload and performance outcomes. For example, physiological measures of workload (i.e., electro-encephalograms (EEG), electro-cardiograms (ECG) or pupillometry) could be used to detect workload changes under different attribute combinations. One might hold-fixed task demand types and levels while varying design features in order to make workload outcome comparisons among different interface alternatives. Other methods listed can also serve as a similar basis for workload comparisons. Surveys such as the NASA-Task Load index (TLX) [23] could be used to assess UAV operator workload along multiple dimensions, based on subjective ratings, in order to motivate specific types of design improvements (e.g., decluttered visual displays for reduced cognitive load or revised control layouts for reducing physical workload). Model-based assessment, such as the use of GOMSL [24], could be applied to analyze operator cognitive processes and quantify the use of working memory. Such measures can also provide knowledge of specific areas of deficiency in interface designs and provide means for formulating design improvements. Likewise, newly developed interface evaluation tools, such as the GEDIS-UAV, can be applied at this stage in order to generate quantitative scores of interface design effectiveness with relation to workload and performance outcomes. The interface design score will be obtained by analyst assessment of a list of optimal UAV supervisory control interface features that address both functional needs and usability. Interface conformance with this checklist will reflect the capability to mediate negative effects of cognitive overload.

In Section 6, we assume a new interface and workload evaluation tool. At the core of this tool is a model of operator workload. The model integrates task demand factors, task scenario factors, individual operator characteristics, and interface design scores weighted by operator interface usage behaviors (as measured in Step 5). In this model some workload/behavior measures serve as predictors of overall operator workload; whereas, others serve as responses for initial model training. Any model of operator workload must be validated and Step 6 involves applying the new tool to contemporary UAV interface designs. Comparison of model-based workload predictions for different interface display feature sets allows for a sensitivity analysis. Furthermore cross-validation of the model in terms of operator performance outcomes is necessary for model use in identification of critical operator states, such as underload or overload in UAV control. Step 6 also involves conducting correlation analyses on model predictions and actual user behavior outcomes for cross-validation of the predictive utility of the new evaluation tool.

## VI. CONCLUSION

The present study presented a constrained review on specific UAV supervisory control interface issues documented in the current literature, identified prevalent interface design approaches, and summarized existing interface evaluation methods. Based on this information, we proposed a research framework for development of a new tool to describe the relationship between UAV supervisory control interface design and user cognitive workload and to provide a basis for enhanced interface design.

By considering the limitations of existing interface evaluation methods and workload measurement and modeling approaches, we plan to formalize a new evaluation tool that can accurately predict interface-induced workload levels and facilitate advanced comparison of different interface design feature sets. It is anticipated that such a tool would be most useful to UAV manufacturers and interface designers but the tool could be generalized to other types of interfaces by substituting domain-specific elements in the checklist.

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