A Multimodal Approach to Design of Aircraft Cockpit Displays

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Abstract: In this paper, we present an approach to design of command tables in aircraft cockpits. To date, there is no common standard for designing this kind of command tables. Command tables impose high load on human visual senses for displaying flight information such as altitude, attitude, vertical speed, airspeed, heading and engine power. Heavy visual workload and physical conditions significantly influence cognitive processes of an operator in an aircraft cockpit. Proposed solution formalizes the design process describing instruments in terms of estimated effects they produce on flight operators. In this way, we can predict effects and constraints of particular type of flight instrument and avoid unexpected effects early in the design process.

Keywords: Aircraft cockpit, multimodal user interfaces, aircraft instrument, formal description of cockpit display.

Introduction

Today's modern aircraft operators rely on vast amount of data that has to be presented in real-time. The meaning of this data is difficult to asses in its raw format. Therefore, we need sophisticated methods to interpret and present data to the user in a suitable format [8]. There is also a need for a data visualization platform that can distribute flight data to a variety of animated graphical displays for easy interpretation by the aircraft operator. Large amounts of airflow velocity data presented in real-time cause numerous effects on human sensory and perceptual apparatus. In situations where the operator must react in a limited period of time and avoid hazardous situations, it is very important to present flight data in a form that can be easily interpreted and processed having in mind user's abilities and preferences. This paper addresses the problem of adapting immense amount of visualization data to the operator in an aircraft cockpit based on the ideas from the multimodal human-computer interaction [11] [12].

This paper is structured as follows. In next section, an overview of the research field and some existing solutions is given. Then, we discuss basic concepts of multimodal systems from the point of our interests. After that, we describe the proposed approach, where we present formal description technique based on the existing metamodel of multimodal human-computer interaction. In Section 4, we demonstrate our solution giving the case study example of Unmanned Aerial Vehicle's (UAV) visual instrument that we have developed. Finally, we give short discussion and conclusions.

Background

In our approach, we are reusing ideas from multimodal user interfaces, and applying them in the designing of aircraft cockpit displays. In this section, we give an overview of these two fields, emphasizing their similarities.

Problem Background

Over the last few decades, the continuous global growth of air traffic has led to increasing problems with respect to airspace capacity and delays [17]. This situation has initiated the research for new operational concepts and aircraft systems that aim for more independent aircraft systems in order to probe the human factors of pilots when operating in aircraft cockpit. Key aspects of this research include modeling interaction in complex time-critical environments like aircraft cockpit and providing timely context-sensitive information in real time without overloading or distracting the human operator [5]. In aircrafts, human-machine interaction is the key issue in providing situational awareness and maintaining safety. The operator functions as an observer who monitors display's information from the flight computer, pays attention to the environment and concentrates on communication tasks. To facilitate the amount of work and tasks he or she has to accomplish, the aircraft becomes more and more computerized. However, the displays in the cockpit of an aircraft can be quite complex and have to function in a harsh visual environment that may strongly affect the quality of the displayed information. Numerous reports and studies clarify specific fields of research such as situation awareness [4], tactile sensation [10], color patterns [3] and so forth. Major drawback of existing solutions is a lack of operational feedback regarding human performances connected with audio, visual and haptic cues in highly interactive environments such as aircraft cockpit.

If we consider interfaces developed in the field of highly interactive (also called post-WIMP) applications, the dynamicity of interaction objects in terms of existence, reactivity and interrelations appears as a new characteristic [6]. These interfaces may include new interactors such as graphical representations of aircrafts at any time during the use of application. Even though this kind of problem is, by programming languages, handled easily, it is hard to master it in terms of models. This is why classical formal description techniques have to be improved in order to be able to describe highly interactive environment in a complete and unambiguous way. The reason for deployment of formal description techniques lies in the fact that they are means for modeling all components of an interactive system (presentation, dialogue and functional module). Besides, they are usually applied to early phases of development process and clarify their limits when it comes to evaluation.

Multimodal Human-Computer Interaction

Multimodal systems represent a research-level paradigm shift from conventional WIMP interfaces toward providing users with greater expressive power, naturalness, flexibility and portability [13]. Multimodal research focuses on human perceptual channels [16]. User communicates with the system through set of communication channels which use different modalities, such as visual display, audio, and tactile feedback, to engage human perceptual, cognitive, and communication skills in understanding what is being presented. Multimodal systems integrate various modalities simultaneously, sequentially or independently, and they are defined by multimodal integration patterns [14].

Various systems offering multimodal interaction techniques have been provided since the early work Bolt in early 80's [1]. Although some real systems have been presented, development process of multimodal interactive systems remains difficult task usually carried out by an ad hoc process.

Previous study on multimodal interaction [8] has shown that multimodal interaction presents several advantages:

Multimodality increases the overall efficiency of interaction. Task-critical errors decrease during multimodal interaction. This advantage justifies the use of multimodal techniques in highly interactive environments (for instance aircraft cockpit).

Flexibility of a multimodal interface can accommodate a wide range of users, tasks and environments-including users who are temporarily or permanently handicapped and usage in adverse surroundings (aircraft cockpit, for example).

Users have a strong preference to interact multimodally. This preference is most pronounced in spatial domain systems when describing spatial information about location, number, orientation or shape of an object.

Multimodality provides greater naturalness and flexibility of interaction that facilitates learning process. This can be very useful for the flight simulator training.

We find multimodal interaction techniques very useful for designing user interfaces in an aircraft cockpit from the point of quantity (they can increase the bandwidth between user and system) and quality (extracting and adapting content according to user abilities and preferences).

For all these reasons, multimodal human-computer interaction appears to be very useful in the field of interactive systems. It permits enhancing human-computer interaction in these systems, but formal description technique is needed to describe entire multimodal interactive system in a way that can be incorporated in current software development practices.

PROPOSED SOLUTION

In this section, we describe how we model aircraft cockpit displays as a multimodal interface. We begin with an overview of the vocabulary of modeling primitives. Then we define basic steps for describing aircraft displays as complex modalities, and describe how these models can be used in evaluating human performances. In the following section, we give a concrete example of a formal description of a visual instrument as a complex modality.

Metamodel of Sensory, Motor, Perceptual and Cognitive Effects

The engineering of multimodal systems introduces additional complexity to the development of interactive software systems, which is rarely addressed by current software development methodologies. For example, the UML Unified Software Development Process [7] devotes only a short paragraph to the design of the user interface. For describing multimodal interfaces we use set of modeling primitives defined by the semantic metamodel of multimodal interaction which has been previously developed [11].

The main concept of the metamodel is a HCI modality, which is described as a form of interaction designed to engage some of human capabilities, e.g. to produce some effects on users. A HCI modality can be simple or complex. A complex modality integrates other modalities to create simultaneous

TABLE 1. CLASSIFICATION OF SENSORY, PERCEPTUAL, MOTOR AND COGNITIVE CONCEPTS

Classification	Concepts
Sensory	Stimulus: light, sound, vibration
	Sensory excitation
	Sensory processing: color, sharpness, peripheral vision
Perceptual	Pattern recognition
	Grouping: similarity, proximity, or voice color or timber
	Highlighting : color, polarity, or intensity
	3D cue such as stereo vision or interaural time difference
	Illusion
Motor	Movement: translation or rotation
	Force: pressure or twisting
	Hand or head movement
	Degree of freedom
Cognitive	Short- or long-term memory and memory processes such as remembering forgeting
	Attention: focus and context
	Reasoning: deductive, inductive, and abductive
	Problem solving: Gestalt, problem space, and analogical mapping
	Analogy
	Skill acquisition: skill level, proceduralization, and generalization
	Linguistics: speech, listening, reading, and writing

use of them, while a simple modality represents a primitive form of interaction. Simple HCI modality can be input or output, using the computer as a reference point. Input and output modalities are not symmetric with human input and output modalities because they represent a computer viewpoint, where it is computer code, not neural circuity that controls interaction with users. Each modality engages some of human capabilities, e.g. it produces some effects on the user. Effects are classified in four main categories: sensory, perceptual, motor, and cognitive (Table 1).

Sensory effects describe processing stimuli performed by human sensory apparatus. Perceptual effects are more complex effects that human perceptual systems get by analyzing data received from sensors. Motor effects describe human mechanical action, such as head movement or pressure. Cognitive effects describe effects that take place at a higher level of human information processing, such as memory processes, attention, and curiosity. Furthermore, effects are often interconnected. For example, all perceptual effects are a consequence of sensory effects. These relations among effects are important because in this way a designer can see what side effects will be caused by his intention to use some effects.

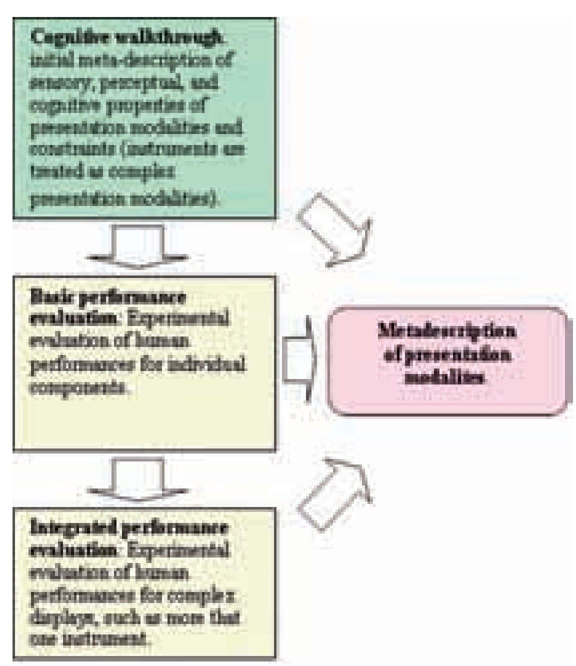
Proposed Approach

Our approach is inspired by the model-driven development, where software development's primary focus and products are models rather than computer programs. In this way, it is possible to use concepts that are much less bound to underlying implementation technology and are much closer to the problem domain [15].

In the design of the instrument table, we have classified instrument types by analogy with modalities as basic or complex. Basic instrument tracks simple parameter values and changes and engages a specific human sense. According to the type of human sensory system it excites, basic instrument can be visual, audio or haptic. Each basic instrument consists of an instrument scale, instrument pointer, instrument zone, and scale marker. Complex instrument integrates other instruments combining information aimed at specific human sensory apparatus into complex and uniform excitation event.

Each individual instrument engages some human capabilities. Communication channel established between the human and system is parameterized by effects produced on the user. By classifying instruments into categories, we can have an insight into specific effects produced by them, which enables predicting effects conducted in complex instruments where various types of signals interfere and integrate. Next step is connecting estimated effects with cockpit environment characteristics and operator abilities that increase or decrease them. In this way, we can treat each instrument as a presentation modality having some inherit sensory, perceptual or cognitive qualities. Thus, a concrete instance of some instrument will add or change some qualities according to user abilities and preferences, for example, by choosing color scheme or shape pattern that can introduce some analogy. Upon these instrument descriptions, experimental evaluation of human performances for individual and complex components is done in order to conclude the metadescription of the presentation modalities as shown in Figure 1. Given the metadescriptions of the presentation mo-

Fig. 1. Proposed design process.



dalities, each instrument is considered as an instance of defined metamodels.

Mapping between instruments and effects can serve several purposes. It provides context where we could perceive many relations that are not always obvious. Predicting effects that an instrument causes on humans and connecting these effects with descriptions of limiting environment characteristics gives an opportunity to avoid some undesired situations which can occur (for example, increasing visual workload during instrument scan). Finally, information channels between users (pilot/operator) and device (the aircraft) are described in a uniform and an unambiguous way.

Design Case Study: A Visual Instrument

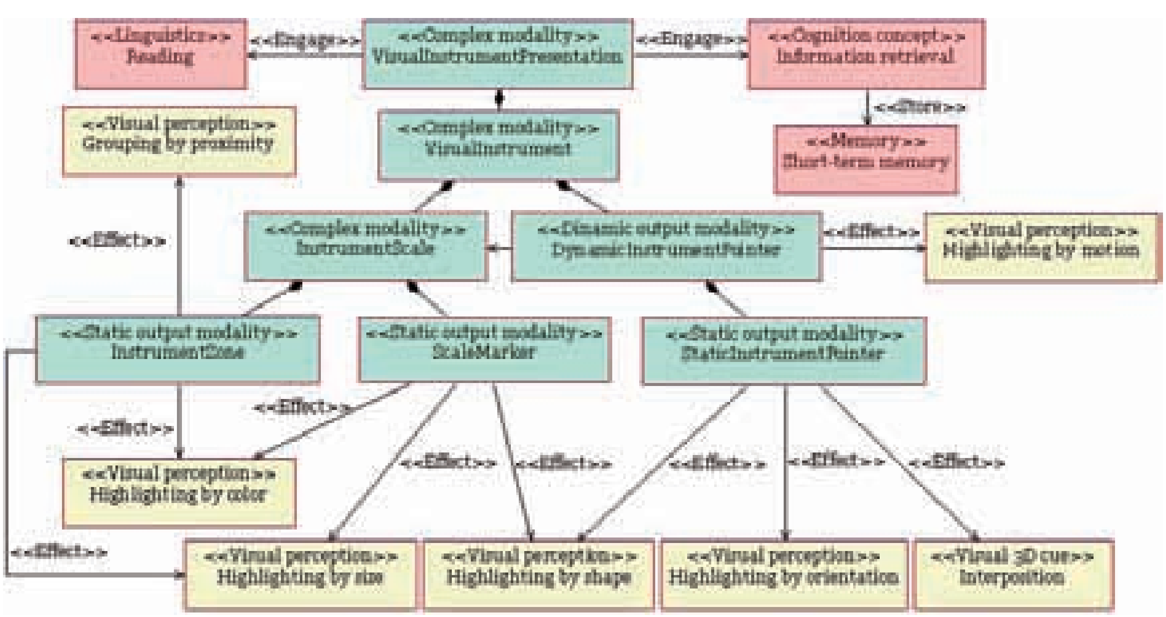
We have applied our approach in designing virtual cockpit for close-range Unmanned Aerial Vehicles (UAV). Requirements for human-computer interface developed are as stated [9]:

- Ergonomic Goal. In order to minimize physical fatigue, the system has to form and fit a human body and to give comfortable environment (temperature and lighting).
- Cognitive Goal. In order to decrease cognitive fatigue, the system should use analog versus digital displays. Placement and font of text and appropriate symbol shapes and colors should minimize scan time.
- Response Goal. This concerns minimizing UAV response time and is achieved by underlying implementation technology.

To realize these three goals we have applied proposed approach. Figure 2 is a UML class diagram, created with defined UML extensions [11], describing the effects of a visual instrument as a complex presentation modality. These effects are used as a basis for achieving our ergonomic, cognitive and response goals. An instrument's basic presentation modality is an instrument pointer that presents the current value of tracked parameter. A *DynamicInstrumentPointer* is modeled as a dynamic output modality animating presentation of the *StaticInstrumentPointer*. Instrument pointers introduce several perceptual effects: it is recognizable by its shape; orientation denotes its current position; and interposition highlights pointer from instrument scale ticks. By smoothly animating positions of the pointer, a *DynamicInstrumentPointer* gives a notion of motion. An *InstrumentScale* defines global extent in which parameter value can change. Scale is presented to the user as a set of *ScaleMarkers* described as static output modalities. Scale markers add perceptual effects of highlighting by shape, size and color. To distinguish between normal and critical extents of parameter values, an *InstrumentScale*

Correct spelling dynamic

Fig. 2. Visual instrument depicted in terms of effects



consists of several *InstrumentZones*, also described as static presentation modalities. Each zone defines local extent in which parameter's value varies. Zones distinguish themselves by introducing perceptual effects of highlighting by color and shape, and grouping proximate of visual indicator for parameter values. A *VisualInstrument* presents complex modality integrating *InstrumentScales* and *DynamicInstrumentPointers*. A set of visual instruments represents multimodality *VisualInstrumentPresentation* which engages human cognitive functions of reading and information retrieval.

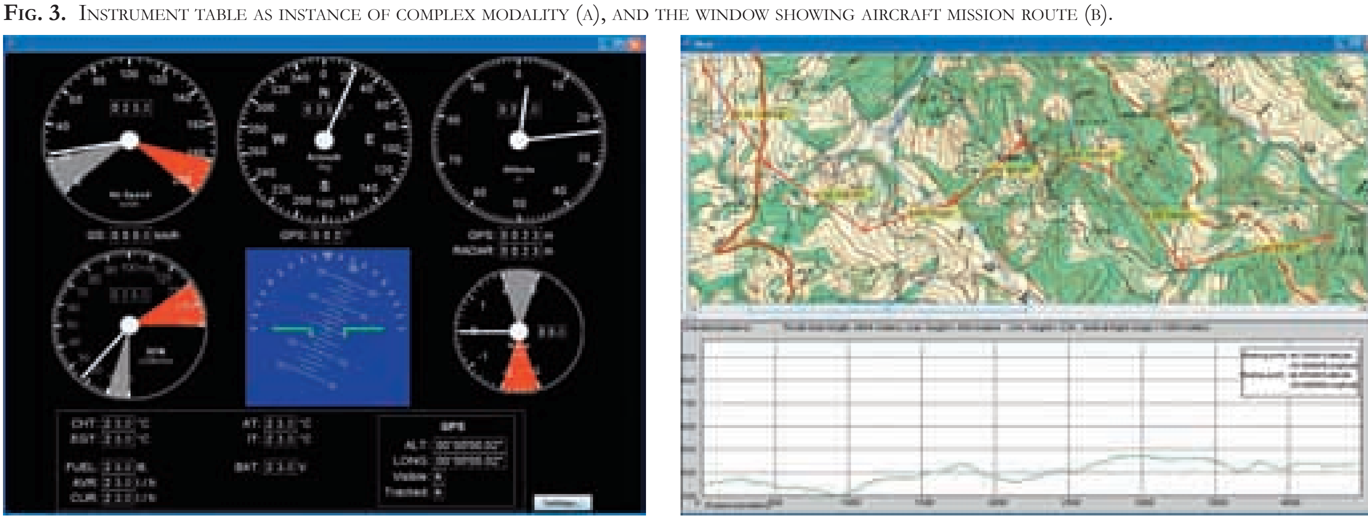
Figure 3 shows instrument table developed upon given metadescriptions. These metadescriptions are most useful in cognitive walkthrough phase, as we have noticed that most of the designers and programmers are not aware of the huge number of parameters that presentation effects introduce by every part of user interface. Presented display operates in a way that represents an operator's intuitive understanding. Controls that have different functions are distinguishable from one another in order to clearly assess flight status data. Instruments and controls with related functions are grouped together in a logical arrangement, which helps reduce instrument scan time and lowers operator's workload.

Discussion

The presented work can serve several purposes. First, we demonstrated the ability to predict effects that certain type of instrument produces on humans. Proposed instrument classification connected with the metamodel of multimodal communication gives us predictive and explanatory approach for describing complex effect notions in an aircraft cockpit and connecting them with user and device profiles. Describing a cockpit in a common language, we facilitate more effective user interfaces. Designing displays and information flow at a higher level of abstraction enables predicting undesirable effects that can appear early in the design and reduces information overload. What is more important it reduces interdisciplinary gap among designers and allows integration of results from various fields of research. For example, multimodal research techniques introduce results that have been used as a basis for a measurement and enhancement of situational awareness [2]. Metadescriptions of instruments as presentation modalities with some sensory, perceptual and cognitive qualities permit experimental evaluation of human performances for complex displays from which users can clearly benefit. Evaluation results allow seeing if concrete aircraft display suits user's abilities and preferences.

Proposed approach describes all effects introduced by the instrument table. However, for more detailed analysis, it is useful to include a notion of a visual scan, which is currently partially addressed by our approach. Visual scan considers a sequence of monitoring tasks associated with flight status. Scan characteristics (where to look, how frequently

Fig. 3. Instrument table as instance of complex modality (a), and the window showing aircraft mission route (b).



(a) (b)

and how long) are currently determined by the complexity of the information provided by devices and level of operator's expertise. Operator/pilot forms a mental model as a comprehensive understanding of a system and its dynamics. However, mental models are refined with experience, so less experienced operator can employ random scan that is not sensitive to the changing needs for information from one moment to the next. Experienced pilots often feel uncomfortable when transitioning to a new aircraft because of a conflict between their mental model and arrangement of instruments in this new aircraft cockpit. Describing cockpit at higher level of abstraction facilitates transfer of operational skills between various systems and avoids negative learning transfer.

The efficiency of usage of our method depends very much on the efficiency of supporting tools. In our current approach, we are relying on the existing UML modeling tools, and their integration mechanisms. The advantage is that the designers who are familiar with UML can do the design in their natural environments. Additional advantage is that the UML tools, such as Rational Rose, enable integration of custom code connecting the tool with other systems. However, the problem with UML tools is lack of rigorousness in modeling, which requires discipline at the side of the designer. Tools that can support analysis of the designed models are a subject of our future work.

In order to take into account the type of aircraft, the level of aircraft operator training, environment, our method allows definition of different models of users and interfaces, at different levels of abstraction. Models can be organized hierarchically and grouped according to different aspects. Models can be reused, which reduces the effort. According to our experience, the creation of the initial model is the most time consuming effort.

In the end, we would like to add that one of the advantages is the increased awareness of the designers and programmers about the human factors involved in the design of interfaces.

Conclusion

The presented work describes an approach to modeling aircraft cockpit devices in terms of multimodal interfaces using the UML notation [11]. This work could help cockpit designers in analyzing the information presentation to humans and avoiding overload as well as streamlining information acquisition. Each instrument consists of one or more modalities (depending on its complexity) and causes one or more effects on the user/operator. In essence, the instrument is a container for one or more information channels between operator/pilot and the device (the aircraft). If we describe the whole cockpit in terms of modalities, we get a unified way of analyzing the inputs and outputs and the resulting effects on the operator (and the device). This can be used as a basis for analyzing cognitive load as well as studying the expressiveness the inputs provide in controlling the aircraft.

We have illustrated our approach on the example of unmanned aircraft vehicle, but it is applicable for manned aircrafts as well. Presented work is a part of ongoing project and is developed as an experimental prototype. In our future work, we plan to integrate our solution into existing CASE tools and work on implementation of tools for designing aircraft cockpits based on multimodal technique presented as a proof of feasibility of the approach.

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