Cognitive Work Analysis and Conceptual Designing for Unmanned Air Traffic Management in Cities*

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ABSTRACT

Cognitive [1] Work Analysis (CWA) is an appropriate approach in high-stakes domains, such as Air Traffic Management (ATM). It provides focus on human expert performance in regular as well as contingency situations. However, CWA is not suitable for the design of a first-of-a-kind system, since there is nothing to analyze before the start of the design process. In 2017, unmanned traffic management (UTM) for intense drone traffic in cities was such a system. Making things worse, the UTM system has to be in place before the traffic, since it provides basic safety. In this paper we present conceptual designing as a bootstrapping approach to CWA for UTM as a first-of-a-kind system.

CCS CONCEPTS

• **Human-centered computing → Interaction design**; *Interaction design process and methods*; Activity centered design • **Applied computing → Operations research**; *Transportation*

KEYWORDS

Cognitive work analysis, conceptual designing, work domain analysis, unmanned aircraft traffic management

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†The full version of the author's guide is available as acmart.pdf document
[1]It is a datatype.

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1 INTRODUCTION

One of the most riveting technology changes in aerospace is the introduction of unmanned aircraft systems (UAS) and remotely piloted air systems (RPAS), commonly referred to as drones. The largest utilization of drones is foreseen to be at low levels with the highest demands in urban environments and cities [8]. This inevitably increases the risk levels. To that end, a considerable challenge lies in how to manage the massive influx of drones, particularly in proximity to humans and to exiting air traffic. The design of an Unmanned Traffic Management (UTM) system for intense drone traffic in cities is particularly challenging since the process itself (the traffic at forecasted levels) does not yet exist. This airspace is currently (in 2018) uncontrolled.

Cognitive Work Analysis (CWA) is an approach well-suited to challenges of high-stakes domains, such as Air Traffic Management (ATM), due to its focus on support for human expert performance both in regular, irregular, and contingency situations. This characteristic is of particular importance in systems that must be monitorable and controllable, where the human is accountable and responsible regardless of automation level—including autonomous system operations. However, with first-of-a-kind system (a completely new system), the CWA analyst is left in a tricky situation, since the basis for making an analysis is weak [5], i.e. there is in the worst case nothing to analyze. There is no current system and no current practices. Some previous work on CWA has addressed novel systems [5, 7]. Our work most closely resembles the work by Naikar et al. [5], which started from a conceptual design. In the UTM case, there is no reasonably complete existing conceptual design either. A regular CWA would have to start with the current ATM situation and apply iterative design to transform it. However, a disruptive technology like UAS on a massive scale, would give rise to completely new conditions of work that operate on a different set of assumptions and with a different control problem. As technology changes radically, tasks also change radically, which give rise to radically new needs and requirements [2]. CWA is like traditional user-centered design approaches a kind of hill-climbing process, which is suited for incremental innovation, but not the kind of radical innovation we see in disruptive technology change [6]. What is needed is instead a kind of conceptual designing, involving framing and re-framing to produce fundamentally new designs to fulfil current goals in new ways, or aim to discover completely new purposes [4, 11]. In conceptual designing, what-if-scenarios are used to frame the design effort in different situations. In this paper, we explore what-if-scenarios that address the question of what services that would be meaningful if there were massive amounts unmanned aircrafts, and what traffic patterns that would give rise to. With that framing in mind, we can then explore the question of how to design a system for the management of the potential traffic patterns.

The basic function of UTM is to keep track of drone traffic beyond line-of-sight from the operators on the ground. In addition to early work on city UTM [9], there are two developments related to UTM for cities that can be used as a starting point for conceptual design. First, there is conventional ATM. One recent estimate from the US is that UTM (using ATM concepts) could require 35 times the current ATM work force [3] already in 2020. Thus, current ATM systems are unlikely to be viable for UTM. Second, there are currently emerging concepts and solutions for countryside UTM [1]. City UTM however differs from these applications by the intensity of traffic and the number of humans on the ground below.

In this paper we will focus on the first activity of CWA, the work domain analysis (WDA). Usually, five levels are used for the process [10], and human concerns [5]. Our WDA (Table 1) starts with some known basic situation (S) as a top (sixth) level then continues with functional purpose (FP), abstract functions (AF), functions (F), physical (implemented) functions (PF), and objects (O).

2 CONCEPTUAL DESIGN WITH CWA

A research-through-design approach, structured by a series of workshops, was used in this project. The aim was to both shed light on the traffic (the core process) and to explore basic building blocks (virtual objects) and the composition of UTM functions.

Table 1: Initial Work Domain Analysis

Level	A to B	Inside Area
S	Drone needs to fly from A to B	Drone(s) needs to operate in specific area
FP	Routing from A to B. Avoid objects	Stay in designated area
AF	Detect and avoid algorithm, efficiency	Border distance calculation
F	Detect, then avoid by going around (lateral avoidance)	Monitor current drone position, versus boundary locations
PF	E.g. LIDAR for detection	E.g. GPS for positioning
O	Drones, buildings	Virtual boundary, drone

2.1 Workshop 1: Services And Traffic Patterns

The workshop identified 140 potential drone services, from transportation to entertainment. From this, some overarching and tentative process characteristics can be hypothesized and used as starting point to bootstrap the design process, through our WDA:

S: Overarching service categories: commercial or recurring operations; peer-initiated operations; high priority irregular operations.

FP: Changing airspace design to match traffic variations: Dynamic concepts for structuring traffic may be useful to match traffic variations. Intensity variations, variations in traffic that have high priority (e.g. emergency services), and traffic pattern variations (due to variations in services) are likely during a day.

AF: Service-dependent priority and value measures: Some of the values and constraints will regard service quality (e.g. a 1-hour delivery should not take more than one hour, emergency services must be given priority). These service-related constraints and values may vary in the system, depending on what services are delivered.

AF: Overarching process characteristics: Both high-volume and low-volume traffic periods were identified, as well as traffic with varying planning horizons.

2.2 Workshop 2: Regulation

The main take-away from the UTM regulation workshop to our WDA was that:

S: Emergency landings and crash behavior was a critical concern. Discussions centered on whether it would be better for drones to crash land on houses, or on roads (in the midst of traffic).

FP: Monitor drone performance limits: to be allowed in the city, the UTM system should ensure that individual drones are reliable within their performance limits, and

FP: Monitor conditions versus drone performance limits: The UTM system should ensure that the performance limits are not exceeded due to variations in environmental conditions (weather) or traffic (congestion).

FP: Contingency management: The UTM system should handle drone-initiated contingencies safely.

2.3 System Concept Design: UTM Building Blocks

The regulatory concerns set the stage for the following steps of our city UTM concept development. Based on previous literature [9] and information on drone traffic in media, four basic UTM building blocks for managing intense high-volume unmanned traffic were identified. We aimed to make them as simple (basic) as possible. Each block combines both a shape to use in airspace design and properties when used to control and monitor traffic.

A *volume* encloses or excludes traffic in an area of operation in an arbitrary 3D shape. Volumes can be used both to encapsulate traffic or restrict traffic. The central notion of the volume is thus encapsulation, the focus of monitoring and control on the borders of the volume, and of entry/exit from it. Volumes can also have a temporal duration. A simplified version of the volume is the *plane*. A plane is a 3D volume that has no edges (for practical purposes) and provides altitude-based separation.

A *tube* (line/trajectory) is characterized by traffic that goes in one or two directions, between two/several points, and the central UTM notion is that traffic is separated by separating the lines It can also be connected to other lines, forming a network.

A moving *point* represents a position in space. For control purposes it usually is given a safety margin around it. It can for instance represent one drone, or a cloud of drones in a moving volume. For control purposes, its central characteristic is that its movements must be monitored in real-time versus other points.

2.4 Workshop 3: Expert Design and Discussion

Based on the UTM building blocks, we developed the following five concepts in a concept design and discussion workshop:

C1 Point-based Control. The participants thought that 2–5 drones realistically could be managed, even though they tentative placed 30 markers on the map. To go above this number, drones would need to rely on autonomous detect-and-avoid. The participants thought that this concept could be used for places with very low traffic.

C2 Airport Exclusion Volume. This UTM concept relies on two simple building blocks: First, a 3D exclusion volume for landing aircraft to the airport. Second, fully autonomous drone traffic outside of the volume.

C3 Grid Squares. The grid was a novel concept not presented to the participants during the workshop. The grid divides a plane into smaller areas (squares). The UTM principle of concept 3 is to monitor traffic versus the capacity of the grid squares

C4 Grid Squares, Exclusion Volumes, Layers. C4 adds layered traffic, in five layers, each with its own grid. Drone taxis (human passengers, PAV) on top was seen as the safest layer. Lowest level for emergency response and similar community services. Levels in between for commercial traffic.

C5 Tubes for Simple or Noisy Drones. This concept focused on drones with low capacity, and on restricting noise by using particular paths. The discussion circled around the complexity that extensive tube usage would result in. They concluded that this concept of direct a–b traffic using tubes was of limited use as the main concept for traffic management, but it could be used for specific operations.

2.5 WDA Workshop Summary

Table 2 summarizes the workshop results in a WDA. The results from workshop 3 are divided into concepts C1–5. The WDA starts with drone traffic situations in cities (WS1). It then progresses with overarching functional purposes (FP) from WS1–2, and the FP of each concept (C1–C5). Some value and priority measures associated with the concepts are also included (AF), the actual designs (F), and the UTM concept building blocks (O) that we identified in our internal workshops and in C3.

Table 2: Resulting Work Domain Analysis

Level	Traffic Management Inside Area
S	*WS1* Drone traffic in cities: commercial or recurring operations; peer-initiated operations; high priority irregular operations.
FP	*WS1* Changing airspace design to match traffic variations; *WS2* monitor conditions versus drone performance limits; contingency management
	C1 Manage airspace with few drones
	C2 Manage shared airspace with airports
	C3 Capacity monitoring, contingency management
	C4 Separation of different kinds of traffic
	C5 Manage simple or noisy drones
AF	*WS1* Service-dependent priority and value measures
	C5 Safety, noise
	C2–5 congestion
F	*C1–5* Composite functions
PF	To be simulated
O	(stationary) volumes, (capacity) grids (*C3*), layers, (trajectory) lines/tubes, (moving) points

3 DISCUSSION

This paper addresses challenges of designing future UTM concepts by integrating CWA with conceptual designing. The conceptual designing included envisioning the future context to understand the work domain and frame the design effort. We also identified a set of core concept building blocks for UTM based on previous work and similar domains. Those included the shape (object level) and potential 'material' properties (focus of control e.g. entry/exit of volumes) for traffic management. This work differs from previous work using CWA (e.g., [5]) in that no UTM concepts for cities were available as a reference, and the process (the traffic) to manage did not exist.

The main contribution of this paper is how to approach this situation by combining CWA and conceptual designing, working toward an interactive prototype (and simulation).

Conceptual design fosters radical innovation by focusing not only on how something should be designed, but also what that should be designed [11]. The framing of potential future situations makes it possible to bootstrap the design process by making strategic assumptions. The framing workshops (WS1–2) and initial design work in the present project served this function Our analysis of the first two workshops identified overarching functional purposes of the UTM system that we did not know before we started (Table 2), as well as an overarching value and priority measure in WS1 (service-based qualities). Whether to address service-based qualities (and not just safety and airspace efficiency) would be an important decision for UTM providers. We thus had to discover new traffic management purposes in order to set functional purposes for the WDA.

Controlling and monitoring air traffic relies on the ability to build an operational picture of the situation. The traffic management workshop focused on situations in the city to manage, and on how to structure the traffic (airspace designs) to make the traffic manageable. For instance, concept 1 was thought to be manageable for one controller with low-capacity traffic, whereas participants designed concepts 2–5 to manage high-capacity traffic. The designs focused on different aspects of control. The grid was a novel concept from WS3 and was introduced to get a better picture of e.g. congestion by dividing the airspace into squares, rather than working with the congestion of the whole airspace. This differs from previous research (e.g. [9]) that focused on capacity of airspace designs, but not controllability. To implement interfaces for these designs, abstract functions (algorithms) would also be needed, e.g. ways to calculate the capacity of the grid squares (and to predict the same), and to calculate (simulate) actual traffic flows to discover particularly congested areas over the days (the process). With this, we return to the initial issue of the paper, that these processes and algorithms did not exist in an UTM system to analyze prior to our design work. This means that our WDA could not be based on analysis of these processes but had to start with envisioning them. To arrive at a more complete WDA for UTM, more work is required. However, this paper has shown that conceptual designing can be a useful way to start working with a WDA for a first-of-a-kind system.

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