Developing Intelligent Agents To Support Air Traffic Control

Johnny K. L. Yuen and **Alonso Vera**
h9604735@hkusua.hku.hk vera@hkucc.hku.hk

Department of Psychology
The University of Hong Kong
Pokfulam Road, Hong Kong

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Abstract

The main goal of this project is to increase the efficiency of and ease the pressure on air-traffic controllers by creating software intelligent agents to provide real-time assistance with their work. To build an intelligent agent we have first conducted a task analysis on the work of air traffic control in order to establish a model of the task. Two separate hours of air traffic control operations were video taped and analyzed in detail. One was a relatively normal hour whereas the other was during a heavy rainstorm that significantly affected the flow of air traffic. Interestingly, the main characteristic of the rainstorm hour was its non-routineness, while the normal hour showed a consistent and regular interplay between the goals of efficiency and safety. Based on the outcome of the task analysis we can begin to assess and diagnose situations where air traffic controllers are more likely to experience cognitive overload. This model will be the reference for building an intelligent agent to support ATC activities.

Introduction

Intelligent agents can be independently functioning computer programs that achieve complex, intelligent seeming behavior, such as learning, problem solving and reasoning, in specific computer-supported domains of expertise. Such agents are intended to track and assist users in their task. The goal of this project is to design an intelligent agent that specializes in air traffic control, equipped with a cognitive model of human air traffic controllers' performance. This model will allow the agent to evaluate the current situation and controller's intentions in the background, drawing the controller's attention when needed. It will also present relevant information to assist the controller to interpret the situation. This is crucial when the cognitive resources of the controller are near limit (e.g., too many commands/requests to/from planes at the same time). In order to equip the agent with a working model of a human controller, it will first be necessary to analyze the knowledge and behavior of human air traffic controllers. We propose to do this utilizing GOMS in combination with a detailed task analysis.

GOMS in Time-Critical Tasks

GOMS (Card, Moran & Newell, 1983) is a method and language to describe how people (typically experts) carry out routine tasks. It models user knowledge and behavior at various levels of description. Describing the goals, operators, methods, and selection rules for a set of tasks in a relatively formal way constitutes doing a GOMS analysis (Kieras, 1999). GOMS is a tool based on an applied information processing model of human cognition designed to describe a task and the knowledge required to perform it. GOMS does not model learning; its nature is to capture expert behavior.

Originally, this technique was used to model user-paced, minimally interactive tasks, such as text editing (Card, Moran, & Newell, 1983; Olson & Olson, 1990). As discussed in more detail below, it has more recently been used to model interactive, externally paced tasks like ship radar monitoring and video games, based on the assumption that there are high degrees of routine content in expert behaviors even when the task is fast-paced and interactive. It is this routineness in content that allows the researcher to break down a task into smaller unit tasks. Furthermore, GOMS models can be used to address specific questions such as time estimates, resource efficiency, embedded goal conflicts, the degree to which goals can be fulfilled, and the flexibility of the cognitive system in the face of ever-changing conditions.

Modeling tools such as GOMS create a knowledge level description of a task (Newell, 1982) and provide a systematic method for decomposing goals into finer details, hence providing the means to predict user goals. Based on such a GOMS model, it is possible to link the performance of specific actions with the knowledge required to carry them out.

A number of studies have shown GOMS's ability to capture the knowledge necessary to predict the course of behavior in highly interactive, complex, time-critical tasks (e.g., John, Vera and Newell, 1994; Vera and Rosenblatt, 1995; Freed, 1998). John, Vera and Newell extended GOMS task analysis to a highly interactive routine task domain -- playing video games. In their research, they first inferred the goals, operators, methods and selection rules required to play a short segment of the game Super Mario Brothers™. The analysis was based on the instruction booklet for the game as well as a task analysis. The GOMS analysis was at two levels, functional and keystroke, and they devised GOMS model at both levels. A detailed analysis of a video taped nine-year old expert playing the game provided behavioral data to evaluate the degree of prediction of the GOMS models. Of the 31 functional level operators predicted, 21 could be unambiguously inferred from the observed behavior, only 1 was inconsistent with observed behavior and no behavior indicated any functions not predicted by the researchers' model. At the keystroke level, of the 62 keystroke level operators predicted, 46 were observed, 3 were consistent with observed behavior, 12 were inconsistent with observed behavior and 35 keystrokes were observed but not predicted. Although the results suggested that the researchers' keystroke level model needed amendment, GOMS was demonstrated to be reasonably well suited for modeling externally paced, highly interactive routine tasks.

Following on this, Vera and Rosenblatt (1995) focused their attention on the task of shipboard radar operations. They created a model of radar operations by decomposing the radar operators' actions into components of GOMS with the goal of developing an intelligent agent based on such a cognitive model. The modeling part succeeded while the agent part did not (primarily because of pragmatic reasons associated with access to the relevant technology). Much of the effort went into defining the unit task of radar operations. The challenge was to create a goal structure that not only focused on a particular contact on the screen, but that also had a high degree of reactivity to new contacts or new information about established contacts. This meant that the methods had to be interruptible when more urgent goals needed to be fulfilled first. Furthermore, returning to the original method needed to be cognitively easy as well. A number of interesting insights arose from attempting to use GOMS for such a highly interactivity routine task. First, a shallow goal stack emerged as a valuable construct, allowing the model achieve high reactivity by quickly returning to the top-level goal after completion of the unit task. Similarly, avoiding using long sequences of methods for the unit task also emerged as an important constraint. This allowed the model to routinely search for information in the task domain in a way that did not impose a heavy demand on working memory when keeping track of the sequence of operators. It also preserved the reactivity and flexibility required to change the current goal (and hence method) when needed. Using the GOMS model, Vera and Rosenblatt were able to identify the parts of the task of shipboard radar control where an intelligent agent's assistance would alleviate the workload of the operator.

Based on their experiences in computer simulation technology and human cognition models, Freed and Johnston (1995) suggested that by focusing on a domain in which the cognitive foundations are reasonably well understood, a cognitive model can prove to be robust enough to be reused even in different domains. The narrow domain of air traffic control allows researchers to apply theories in perception, motor movements, speech productions, as well as higher-level cognition like decision-making, in building modules for this model of cognition. This model can be used to address contexts in which particular cognitive modules misuse mental resources, employing unreliable methods or are simply too slow to generate an output, which will elicit chain reactions in subsequence performance.

Air Traffic Control

Modern air traffic control is carried out primarily with the aid of computers. Computers receive, organize, present and transmit flight information from one air traffic controller to another. The role of an air traffic controller is to coordinate the airspace according to this information, so that airplanes can navigate safely and efficiently. The cognitive workload typically imposed on air traffic controllers is high even though they are assisted by computers. Air traffic controllers build up a mental picture of the air traffic from the information displayed to them on their radar screens, flight strips, radio channels as well as the coordinator. Depending on the specific configuration of the airspace, the controller lines up the planes from different air routes into a designated trajectory. In parallel, the controller constantly updates his mental representation of the air space and projects traffic into the future in order to forward-plan the flow. The busier the traffic or the worse weather conditions, the less time and cognitive resources are available for the controller to spend on a particular aircraft.

In theory, the task of air traffic control can be construed as routine problem solving by an expert. Describing it as problem solving has an important consequence: it can be decomposed into several elements that constitute the task: there is a Goal, which represents a difference between current state and desired state, and beneath it sub-goals which represent state differences in finer detail. There are sequences of steps that need to be carried out in order to achieve those goals. In the ATC domain, the controller's sub-goals are to *safely* and *efficiently* coordinate air traffic in the air space for which they are responsible. Current conditions (e.g., traffic, weather) and distance of aircraft from the airport constrain which command the controller can issue at any given moment to a particular aircraft. One level deeper, the operators used to achieve the required sequence of steps (i.e., the methods) will include track-balling, keyboard inputs, mathematical calculations, and issuing commands.

A central characteristic of the task of air traffic control is that controllers do not control the pace of their work; on the contrary, it is externally paced and highly interactive. Their actions are largely determined by what is happening out there and they plan and react accordingly. Their attention to a particular plane may consequently be interrupted at any moment. They are constantly issuing commands and receiving feedback. Controllers interact with pilots in order to issue and verify commands. In parallel, they interact with the computer console in front of them in order to plan and monitor traffic flow. Integrating these two activities, especially when conditions are poor and cognitive load high, turns out to be one of the more difficult aspects of the task.

Structure of the Research Project

There are two phases in current ATC project. The first phase involves establishing the *unit task*. In this phase, the researchers have gathered data on the task of air traffic control in order to determine the short sequence of actions that is iterated in order to achieve the task as a whole. Most tasks where experts perform well-learned behaviors contain such a *unit task.* This short sequence of routine behaviors allows controllers to work on a number of different objects in parallel, thus helping overcome the limitations imposed by short term memory and attention. Site visits to air traffic control facilities, studying of written materials, interviewing controllers, and studying playbacks of real air traffic control scenarios have been the main sources of information.

In the second phase of the research the unit task model will be transformed to be the knowledge base for the intelligent agent program that will be implemented within the computer systems of an air traffic control station. Among other things, it will provide a means for the agent to evaluate and predict the users' memory and attentional load and hence give appropriate assistance.

Current Findings and Discussion

The researchers have spent 20 hours observing air-traffic control and talking to controllers over the past two months at the TRACON (Terminal Radar Approach Control) Operation Center at the Hong Kong International Airport. The new Hong Kong airport at Chek Lap Kok opened in July 1998 with just one runway (Southern or "07") in operation. The Northern (or "25") runway started full operational use on August 31, 1999. Both runways are 3,800 meters in length and 60 meters wide. Depending on daily weather conditions, the Hong Kong Civil Aviation Department decides which Runway, 07 or 25, to used.

Up to this point, we have focused on studying the approach sector of Runway 07. Runway 07 is of particular interest due to several factors. First, it is the physical structure of the air space. Due to the shape of the airspace and the location of the runway (see Figure 1),

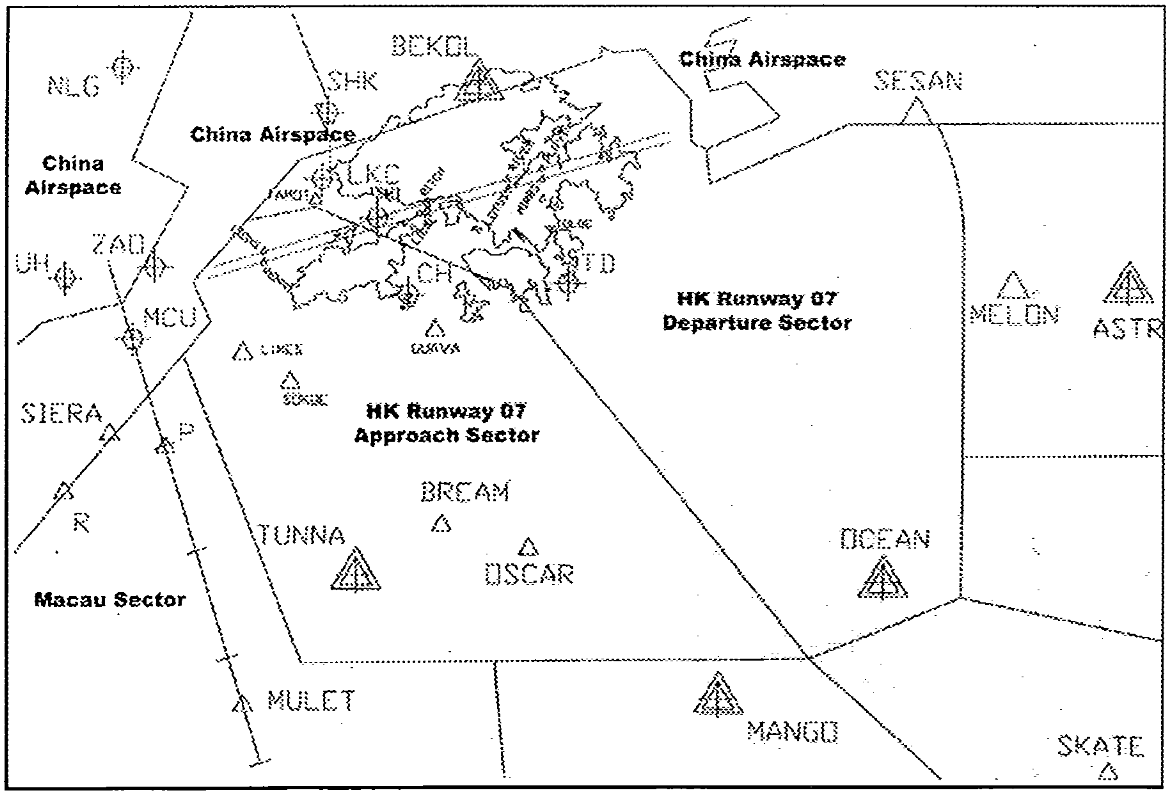

Figure 1. Airspace around Hong Kong.

approaching planes to Runway 07 need to make a 40 degree turn (see Figure 2) before establishing their final descent. For this reason, planes from different air routes in the approach sector need to be lined up in a single cue around 10km before the 040 turn. Secondly, due to the proximity of Hong Kong International Airport, Macau International Airport and China air space, there exist a buffer zone through which approach planes should not fly under normal circumstances. Planes need to be handed off to the controller of the other air space if they cross the buffer zone. As a result, the controller of the approach sector in Hong Kong will not issue commands for planes going into that area.

These two factors constitute the major built-in constraints in supervising this approach sector in Hong Kong. Runway 07 approach is the busiest sector in the Hong Kong air space and the task itself is most sensitive to external factors such as weather, individual pilot differences, position of the planes and so on. The task is cognitively demanding and even more demanding under bad weather conditions.

Two hours of operations were video-taped for detailed analysis. The two separate one hour periods were selected. They were the same hour on different weekdays -- 11:00am to 12:00noon on a Tuesday and on a Thursday. Runway 07 was used on both days, such that the same set of rules and approach procedures applied. The main difference between the two days was weather conditions. One was a clear sunny day (*normal hour*) while on the other day there was a heavy rainstorm centered over the approach sector (*rainstorm hour*).

In the task analysis, the researchers first transcribed all the radio communications between pilots and the controller. A log sheet was designed to record audio communication as well as visual information, e.g., track ball movements, information presented on the monitor, position of the planes over the approach sector and so on. The researchers spent a few weeks getting as much information out from the recordings as possible. The log sheet will be used to assess controllers' cognitive capacity against the workload, based on the data

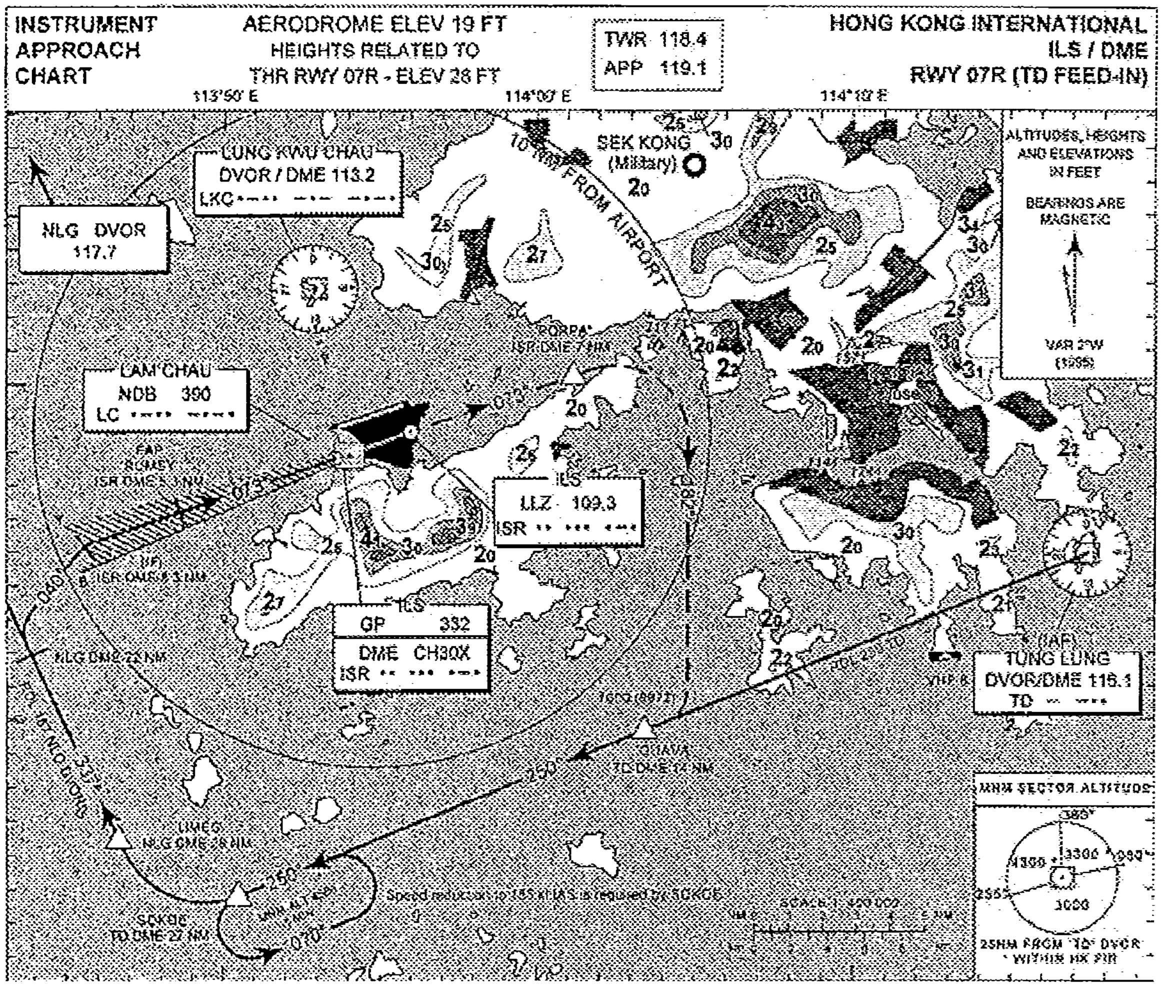

Figure 2. Overview of approach to Runway 07 in Hong Kong.

obtained from the task analysis. In order to complete the first phase of the research and start the second the unit task will need to be extracted from these protocols.

Since the major difference between the two hours was weather conditions, we found that during the normal hour, the task was very routine. The controller received planes, guided them through the sector, lined them up for the final 040 turn, and handed them off to the tower after the plane was established on the runway. However in the rainstorm hour, the controller needed to negotiate with the pilots back and forth for the appropriate headings and altitude since the controller could not see the actual weather conditions and pilots have negotiating rights under such conditions. Worse yet, a number of planes requested non-designated flight paths for their descent. As a result, the controller needed to deal with non-routine requests as well as the routine aspects of the task during the rainstorm hour. This imposed greater cognitive demands on the controller.

The findings from coding the two one-hour scenarios are summarized in Table 1 below. The numbers of planes handled in the two hours are about the same, and the number of planes landed (handed off to tower) was the same in the two hours. There was one striking difference however. Much of the additional resources spent in the rainstorm hour was devoted to answering requests and negotiations. The rainstorm hour was characterized by its lack of routine, introduced by the large proportion of discussion and negotiation between pilot and controller,

	Normal Hour	Rainstorm Hour
Number of planes handled	22	20
Number of planes landed	11	11
Total time used for communication in one hour (in seconds)	720(controller)+745(pilot) =1465	928(controller)+1060(pilot) =1988
Number of radio call by	157(controller) 174(pilot)	236(controller) 254(pilot)
Number of communications devoted to answering requests or negotiation	**3**	**57**
Number of commands related to altitudes	73	74
Number of commands related to headings	65	70

Table 1: Summary of observations from the two video-taped hours of air-traffic control activity.

often initiated by the pilot. What makes the rainstorm particularly cognitively demanding is that the controller's task becomes largely non-routine.

On more than one occasion safety and efficiency were found to be competing goals. We found that in the normal hour the controller often changed the headings of planes to 270 several miles after the TUNG LUNG DVOR/DME (Figure 2) instead of following the designated air route heading 250. There were also other shortcut flight routes issued by the controller. These actions shortened the distance, hence shortened the time for the plane to land and lead to higher efficiency. We initially hypothesized that, during the rainstorm, the controller would stick to the designated air routes stated in the Honk Kong Airspace rulebook. This did not turn out to be the case. What the controller did in that rainstorm hour was to negotiate with the pilots for the best flight paths since he could not see the actual conditions. The controller consequently could not stick to the book for routines and therefore the task became much more demanding. This opens up the possibility that a cognitive model-based agent can assists with the routine aspects of the task in difficult conditions allowing the controller to deploy his cognitive resources exclusively or largely to the non-routine components.

We are currently working toward extracting the unit task by identifying the recognize-act cycle from the radar screen and audio communications in the *normal hour*. By identifying the routine content in the normal hour we can begin drafting the knowledge model for an intelligent agent. While intelligent agents are good at routine tasks, they tend to fail in non-routine situations. An ATC intelligent agent can assist the controller with the routine aspects of the task under cognitively demanding conditions thus sparing cognitive resources for the controller to deal with non-routine aspects during such situations.

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