Cognitive Analysis for Knowledge Modeling in Air Traffic Control Work

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Abstract. Air Traffic Control systems are a kind of service which allows controllers from the ground to keep aircraft safely separated to avoid collisions. It is important to use cognitive systems for the development of this type of critical system. Systems should not only have high performance functions, but also have better user friendly functions and accessibility. It can be said that we have to analyze the functional elements in the work of systems design. To design more reliable interfaces or training programs for the provision of ATC systems, we need to understand the details of basic functions of air traffic controller's tasks within the system. In this research, we discuss the analysis of ATC tasks and modeling of the knowledge of air traffic controllers. And then, we attempt to formalize the basic knowledge of controllers to help them to have a good understanding of the knowledge structure and logical relations.

1 Introduction

Air Traffic Control (ATC) services need to be smoother and more efficient in order to respond to increasing air traffic demands. In current ATC systems, air traffic controllers control air traffic flow by way of their decision making using computer tools.

Air traffic controllers are expected to provide services to keep the air space safe and maintain smooth air traffic flow On the other hand, as the work and tasks of controllers become more complex and the volume and types of information required to carry out these tasks becomes increasingly greater and more complex, the need for systems that are designed to support controllers becomes greater (Banks, 2002). Thus, supporting systems are necessary to enable appropriate cooperation between air traffic controllers and systems in the performance of ATC work in the near future.

With human-machine systems, it is important that design consideration is given to each role and relationship between the human and the machine in order to achieve appropriate cooperation. This is also a key issue for design in ATC systems. On the other hand, however, it is difficult for designers and developers to understand the knowledge content of air traffic controller work, with that knowledge being highly specialized.

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Besides acquiring basic knowledge, air traffic controllers undergo simulator training to gain sufficient experience for the acquisition of specialized knowledge and skills. The knowledge needed for ATC operation is not sufficiently formalized, as a large part of ATC operation depends on the experience of each Air Traffic Controller.

We see a need to analyze and model structures of objective work to understand this tacit knowledge and skills. In this research, we first discuss the task analysis method based on distributed cognition for analyzing the real situation of ATC. After that, we also discuss the framework of knowledge management for Air Traffic Controllers. In this research, we attempt to formalize basic controller knowledge to facilitate the controllers' understanding of knowledge structures and logical relations. The aim of this project is to study the applicability of distributed cognition to such knowledge management tasks, with the objective of developing a systematic framework to represent knowledge relevant to ATC expertise for support.

2 Cognitive Process Perspective in ATC Systems

Future air traffic control systems will become more complex and more accomplished by including the element of management. The cognitive systems approach plays an important role in the development of such complex systems. However, even if s systems is complex, they do not need to have many high performance functions, but should always be user oriented and provide greater accessibility. So, there is a need to analyze the functional elements for designing systems. In order to design a system that can assure system safety, enhanced usability, and increased operator reliability, it is critical for the developers of ATC systems to consider the specifics of how the control system is operated, as well as the cognitive characteristics of controllers.

Automation tools have been used as effective support tools in various industrial sectors. However, human error occurs when the mutually dependent relationships between controllers and machines break down. A promising strategy for systems to assist in task performance is the concept of cognitive systems that try to enable human-systems interactions in a knowing manner that is similar to the way in which humans interact with one another (Forsythe et al, 2006).

Such systems require a user model that explains user behaviour from various aspects of cognitive processes such as awareness, memory, user knowledge and experience, context recognition, planning, intention formation, and even consciousness. User models can be used to predict a users' cognitive processes which in turn can be used to better support them (Haikonen, 2003).

In particular, from the cognitive process perspective, it is essential that systems developers understand the complex working processes that are involved in cooperative work by multiple controllers.

However, little has been studied about the cooperative work of air traffic controllers using analytical methods. Since air traffic controller skills are acquired through specialized training, their cooperative work processes are very complex and temporal constraints are also very restrictive and severe. In order to design and develop more reliable systems or training programs for controllers for the future ATC systems, we need to understand the details of the basic system (including controller) functions.

Distributed cognition is a methodological framework by which to analyze the cognitive processes that span multiple actors mediated by technology (Hollan et al, 2000). Distributed cognition can be effective in analyzing cooperative work from the cognitive process perspective. A central tenet of distributed cognition is that cognition should be regarded as a property of a system of individuals and external representational artifacts carrying out cooperative activities (Fields, 1998). Distributed cognition analysis makes explicit the dependencies between human actors and artifacts by examining the transformation and propagation of information through the various forms of representations. As such, 'knowledge' can be represented in terms of interactions in context, which lends itself to further analysis. The management of knowledge, and hence the retention of knowledge, is through changes in distributed cognition induced by the introduction of new systems, personnel, and norms.

3 Task Analysis Based on Distributed Cognition

3.1 Distributed Cognition

In this research, we attempt to analyze and model interactions that take place in current en route ATC work based on distributed cognition. We have taken the activities of a cooperative team of en route controllers as our unit of analysis from a cognitive process perspective. We discuss the application of ethnographical analysis in en route controllers' work as a team, and report on the findings from our ethnographical analysis, followed by a description of analytical models.

An ethnographic approach can be effectively applied when the problem involves the analysis of what knowledge and experience people use in the context of cooperative work. Ethnomethodology is a method of sociology for determining the implicit orders, rules, or norms behind human activities through observation in the actual work environment.

In this paper, we focus on the factors of team performance. As a first step, to analyze how air traffic controllers work, we carried out data collection through the observation and recording of actual work activities in the Tokyo Area Control Centre (TACC) control room.

3.2 ATC Work Setting

We observed that there are some specific and characteristic points in ATC work; in particular, the basis of that work is prediction and instruction, to secure and maintain a safe traffic situation.

Air traffic controllers control air traffic separated into many distinct areas called sectors and more than two controllers are allocated to and take charge of each sector as a team. Usually one controller takes the role of radar controller, and the other takes that of coordination controller. An additional controller will join in for a busy sector, but twin controllers as shown in Fig. 1 are assumed for this work.

Fig. 1. Working situation of Japanese en route ATC

We carried out observation during a time period of relatively heavy traffic that imposed a certain level of workload on the air traffic controllers. Two fixed video cameras were used for recording the behaviour of the controllers at work, and another was used for recording the radar screen of an auxiliary control console that displayed the same radar image as the controllers were looking at on their work console. A digital audio recorder was set up above the control console to record conversations between the radar controller and the coordination controller. In addition, radio communication between the radar controller and airplane pilots, and between the coordination controller and different sectors, and traffic data such as the position, ground speed, and altitude of aircraft, which were displayed on the radar screen and stored in the control centre computer , was obtained.

In our case, the target of observation was a sector called "Kanto-north" (T03) shown in Fig. 2, which spreads over the northern area of Tokyo. The radar controller in en route control predicts and estimates traffic from five to ten minutes into the future. Meanwhile the coordination controller elaborates on these instructions to keep

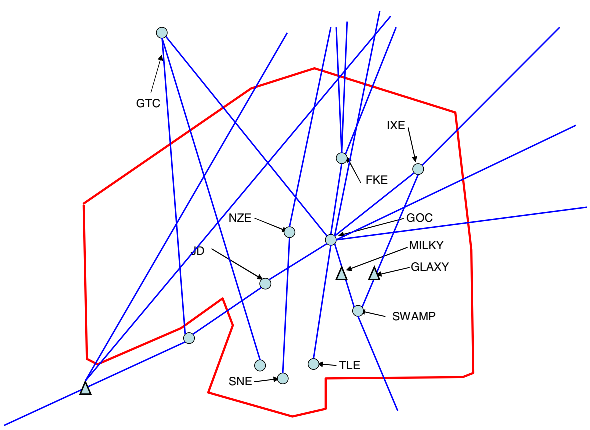

Fig. 2. Kanto-north sector

a safe separation of aircraft based on current information. Many interruptions occur when the controllers have to handle more than two aircraft at the same time: calls from other aircraft outside the immediate focus, requests for handoff from another sector, etc. The coordination controller, who has similar tasks to the coordinating tasks of neighboring sectors, also has to deal with interruptions. In addition, the controllers have to control all IFR aircraft in their own sector. Since en route ATC work has to deal with a variety of states and conditions in their sector, it differs significantly from well formalized tasks such as assembly line operation.

3.3 Data Gathering for Analysis

In this observation, we recorded motions and sounds by video, and system logs as basic data for the analysis. From these we reconstructed the controllers' actions and protocol logs, and analyzed the controllers' tasks in each situation. The system had functions to record multiple types of time-series data such as video, audio and operation logs. We obtained this data for a total of 6 hours by spending 3 days in observation.

Video data
The Video recorded the air traffic controllers' behaviour such as instruction, and coordination, etc., in the control room. Cameras recorded the entire control room from three directions including the radar screen, the flight-data-strip bay, and the view from the back of the room. Moreover, we combined the video from all of the cameras and the audio from the radar controller, the coordination controller, and the pilot, synchronized them, and then recorded them in a batch.

Flight-data-strip
Markings, notes, etc., for flight-data-strips are written by the air traffic controller during their control work. We can find clearance data and instructions for individual airplane pilots and the content of coordination with other sectors in the records on these strips.

3.4 Overview of Data Analysis

In the analysis of the video data, audio data, and radar screen images, they were firstly combined into a single track of video-audio data with synchronized time stamps. Radio communications and conversations among ATCos were then transcribed, and the speakers and listeners of these conversations were identified. The actions of controllers were next recognized from the video data and added to the transcribed protocol data. The data derived from these conversational records and behavioral records, and so on were segmented by the basic units of ATC instructions. With the help of a rated ATCo, we clarified the relationships between the segments and identified the expert knowledge and judgment behind them. This analys showed that Rader Controller and Coordination Controller shared control strategy and team intentions through both verbal and nonverbal communications and established mutual beliefs on SA. These processes lead to smooth cooperation in en-route ATC.

4 Definition and Description of Knowledge

It is not easy to acquire the knowledge needed for ATC work as ATC operations are complex and performed as a team. To codify and manage this knowledge can assist in effective knowledge acquisition. However, explicit knowledge is only part of the whole. Therefore, we need to examine what knowledge is tacit and what knowledge is explicit in ATC work. This chapter will discuss the definitions and representations of knowledge.

4.1 Theory of Knowledge Management

Within the general concept of knowledge management, there is "tacit knowledge" and "explicit knowledge." Tacit knowledge is individual knowledge which is personal and context-specific. But, such knowledge is difficult to formalize and communicate concisely to others.

On the other hand, explicit knowledge can be represented by a formal, logical, systematic language (Polanyi, 1958). Polanyi wrote that "human beings acquire knowledge by actively creating and organizing their own experiences." Given this concept, knowledge that can be represented by systematic language or symbols is part of overall knowledge. Tacit and explicit knowledge are closely related; however, they each have different aspects. Tacit knowledge is subjective while explicit knowledge is objective. Nonaka and Takeuchi (1995) refer to explicit and tacit knowledge, saying that "the dynamic model of knowledge creation is anchored to a critical assumption that human knowledge is created and expanded through social interaction between tacit knowledge and explicit knowledge," and that the process, called "knowledge conversion," is cyclical and mutual. Knowledge conversion forms a process of transformation called the “knowledge spiral,” shown in Fig.3. This cycle is a dynamic process in organizational activity (Nonaka et al. 1994).

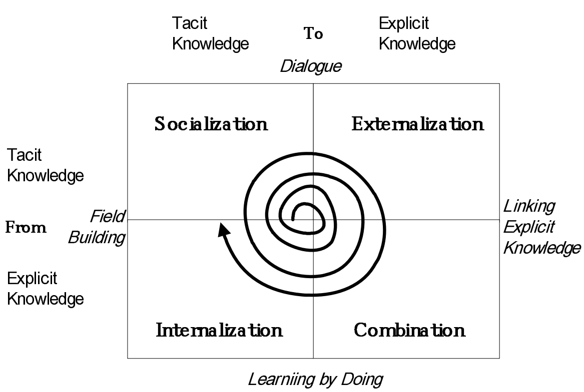

Fig. 3. Four modes of knowledge conversion, and the knowledge spiral (Nonaka & Takeuchi, 1995)

One purpose of codifying a systematic structure of knowledge is to assist the transformation process of these modes of knowledge. In order to formalize the knowledge of air traffic controllers in ATC work, it is important to analyze the relationships between work processes and to understand the specific content of tacit knowledge and explicit knowledge. In the next section, we will discuss knowledge forms in ATC work.

4.2 Composition of Knowledge

If we learn to master technical skills and special knowledge, to demonstrate the good performance of a system that includes humans, there must be a formal, systematic, codified training program in which logical thinking, experience and skills are combined. The knowledge conversion process can thereby proceed smoothly and efficiently by formalizing the theory and experiences described in the previous section. The framework should enable the efficient organization and acquisition of special knowledge and skills by assisting in the process of knowledge conversion, such as the tacit knowledge creation or acquisition of explicit knowledge. Air Traffic Controllers have special knowledge and skills for carrying out ATC operations. We therefore consider knowledge management by Air Traffic controllers to be an important element for the future in ATC systems from the perspectives of safety and training.

In ATC work, air traffic controllers learn about conventional rules and technical regulations which they first encounter in manuals. They then acquire basic knowledge of and skills for control operations through iterative simulator training. After that, controllers learn specific rules, technical regulations, and orders for the sector where they will be in charge of operations. They finally qualify as controllers after acquiring through training the knowledge and skills needed to perform operations in the sectors where they will work. Here, explicit knowledge such as rules and regulations are captured and provided to the controllers as documents, while tacit knowledge is acquired through the training and application of learned knowledge in developing their skills. As such tacit knowledge is more embedded in the context of work and depends on audio-visual perception, situational awareness, and norms that are not easily represented and captured. The following definitions elaborate on explicit knowledge and tacit knowledge as used in this study.

Explicit knowledge
Knowledge that can be written in a systematic language in a document. The most basic ATC operational information is written in the form of regulations and rules. Moreover, knowledge which can be described in a systematic language following analysis and evaluation is assumed to be explicit knowledge, even if the knowledge is based on empirical measurements or techniques involving the exercise of an individual's skills.

Tacit knowledge
By analyzing and arranging the data pertaining to knowledge and skills, there are some types of information more easily understandable as non-linguistic visual or aural stimuli than in a systematically linguistic form. Knowledge or skills of this type, such as situational awareness, temporal awareness, timing of actions, and interaction

through space, are defined as tacit knowledge, which is difficult to represent linguistically.

4.3 Representation of Explicit Knowledge

We have examined the work of controllers in terms of distributed cognition, and analyzed task-flow knowledge. We will now discuss the development of a knowledge structuring tool which focuses on the management of explicit knowledge. We report here some results of our attempt to formalize and express explicit knowledge, which forms part of the development of a knowledge management framework.

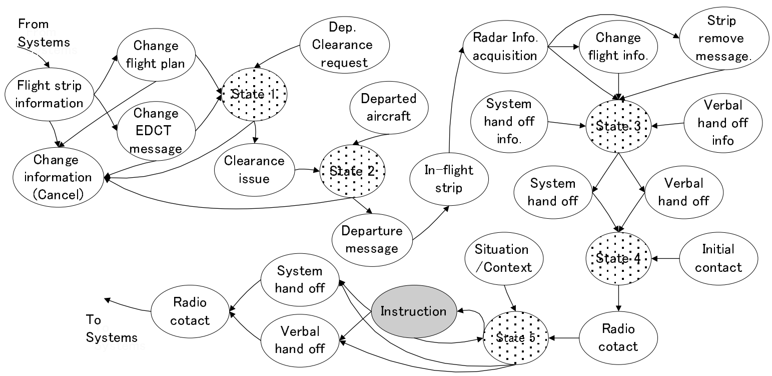

Fig. 4. Concept level of knowledge network diagram in ATC work domain

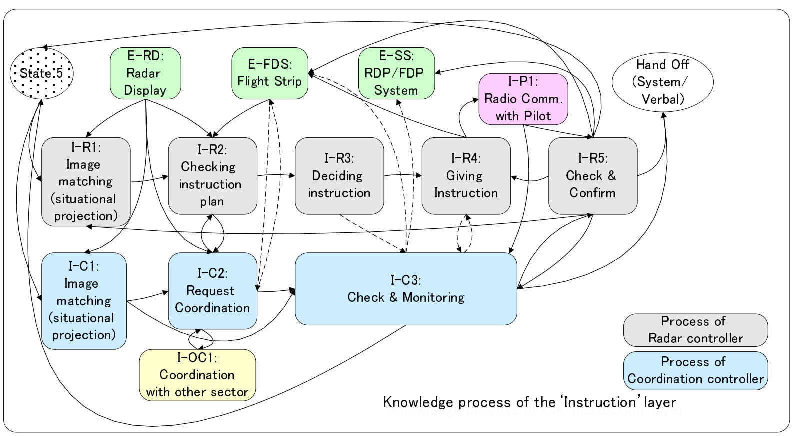

Fig. 5. Knowledge network structure into the "Instruction" layer

The relationships between the forms of knowledge that are applied in ATC work is represented in Fig.4 and Fig.5 as a knowledge network, formulated on the basis of observation and interviews. ATC task processes are expressed as state transitions in the knowledge network. The knowledge network has a layered structure, but how the structure is layered depends on how the knowledge is quantized. In this regard, appropriate quantization techniques are not discussed. The advantage of having a task-flow clarified by distributed cognition analysis expressed as a network of knowledge is in being able to arrange the relationship between the form of work an air that an traffic controller engages in and the information that he/she uses. It is difficult to arrange information regarding the means of use of an entire body of knowledge, because even if each state uses the same information, when expressing it in a task–flow diagram that information has to be described discretely for every state; however, by using a knowledge network, it is easy to understand the state of the information use, as each state is arranged by describing its relationships with other states in relation to that state. Moreover, it is effective in that tacit relations are re-written as explicit knowledge, thus clarifying till then unseen informational relationships. We attempt to describe this knowledge structure using the prototype tool of the knowledge management framework.

ATC knowledge is roughly divided into 2 types: knowledge about rules and regulations, and knowledge related to skills for operation. We tried to make a model of skills knowledge analyzed using distributed cognition: a tool to describe the classifications and knowledge relationships by tagging each state of a node in a knowledge network. In addition, the rules for the task process, which are in turn invoked by the trigger of state transition, can be described as system properties at the node. The conditions and parameter items which describe the system properties can be considered a knowledge model of the decision making process for air traffic controllers. We consider the tagging of system properties to be effective in shedding light on the relationships between, and attributes comparing, other processes. Codifying and managing system property tags as knowledge has promise for the standardization and improvement of training. As a result, we believe that distributed cognition analysis can contribute to improved reliability in controllers and safety in ATC systems.

5 Conclusion

Distributed cognition is applicable to knowledge management tasks where the objective is to develop a systematic framework representing knowledge relevant to ATC expertise. We have proposed a technique for knowledge management as an approach to the study of problems relating to the human factor in an ATC system, and to the structuring of ATC tasks in order to overcome these problems.

The formalized techniques of explicit knowledge have already been covered above; however, the issue of how to represent tacit knowledge in our frame-work of knowledge management remains to be addressed. An approach that describes and represents information in the form of images, a movie or a role-playing simulation (such as a serious game) may be necessary in acquiring knowledge which is difficult to describe or understand in a linguistic form. Learning from a story of a situation can be effective in acquiring tacit knowledge. We are still examining the issue of the representation of tacit knowledge for a future project.

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