Air Traffic Control Command Monitoring System Based on Information Integration

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Abstract—**With the increasing demand for air transportation, all parties involved in the air transportation system have increased their efforts to make the system more efficient without sacrificing safety. This paper presents a new system based on information integration, the Air Traffic Control Command Monitoring System (ATCCMS), which integrates all kinds of fundamental information such as radar information, flight plans, voice communication, and weather conditions into a comprehensive information platform. In this paper, the context of voice communication is analyzed with speech recognition technology and is correlated with radar data and expert knowledge to determine whether any potential danger will emerge from the controller's instructions. Simulation experiments show that the safety level of air transportation systems will be effectively improved by the use of the information integration technique. The prototype of ATCCMS is under test run in North China Regional Air Traffic Management Bureau of CAAC.**

Index Terms—**air traffic control, conflict detection, speech recognition, information integration**

I. INTRODUCTION

To provide separation service for civil flights is the primary task of air traffic control. Aviation safety is the basis of expediting air traffic flow and improving the profitability of civil aviation transportation. Along with the rapid increase in air traffic flow in China in recent, air traffic controllers' workloads have been so greatly

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increased that man-made mistakes that threaten flight safety frequently happen. Although technical innovations in communication, navigation and surveillance have progressed and on-board safety devices, such as the Traffic Alert and Conflict Avoidance System (TCAS), have been gradually perfected, one problem that remains is to develop an efficient auxiliary automated system for air traffic controllers, which will act as an intelligent supervisor with the functions of monitoring daily air traffic control operations, alerting human controllers to possible man-made errors and ultimately ensuring flight safety.

As described in [1] and [2], information integration, the driving force of this decade of IT (information technology) spending, is a technological approach that combines core elements from data management systems, content management systems, data warehouses, and other enterprise applications into a common platform. Based on the information integration technique this paper presents a new system for air traffic control, the air traffic command monitoring system (ATCCMS), which can reduce the controller's man-made errors and ensure flight safety. Some key components of ATCCMS are discussed in following sections.

The paper is organized as follows. Section II introduces the safety problems in air traffic control. Section III presents the design objective of ATCCMS. Section IV and section V present the function architecture and logic architecture of ATCCMS, respectively. Section VI presents analysis and experiments on key components of ATCCMS. Section VII gives the conclusions of this paper and comments on future work.

II. SAFETY PROBLEMS IN AIR TRAFFIC CONTROL (ATC)

During busy aviation activity, the concentration and stress of human controllers are so heavy that their mistakes are an important source of danger to flight safety. Most mistakes are related to the controller's speech instructions [3].

At present, TCAS has become the standard device for current civil aviation aircraft, which can effectively provide the pilot with potential conflicts and advice in order to avoid collision. For the controllers, there are several sets of new air control systems and aided-command systems to choose from, such as the AutoTrac system of Raytheon, the international airspace management system of Hughes, the EUROCAT of Thomson-CSF, the ASTEC system of Lockheed-Martin, and the CTAS of NASA [4]. Most of these systems comply with the CNS/ATM standard of ICAO [5], and have common characteristics such as wide-screen high-differentiability-rate controller workstation, friendly graphical user interface (GUI), and functions such as radar data processing (RDP), flight data processing (FDP), automatic dependent surveillance (ADS), and conflict detection and alerting. For flight safety, however, the following flaws exist in these systems: (1) speech instructions are not recognized as an important data source so that controllers' behavior cannot be monitored, and hence alerts for the danger resulting from false instructions can not be given in advance; (2) high-level flow management is not combined with conflict avoidance.

The process of ensuring ATC safety may be regard as the one that ensures the basal information to be transmitted quickly and to be processed efficiently so as to provide good decision-making information. There are two ways to improve ATC safety.

One is to upgrade the unit technique in the air traffic control system, such as the radar and controller workstation. This requires great investment and a long time period, and cannot improve monitoring of the controller's voice communication.

The other is to use integration technology, which includes two steps. The first step is information integration. With computer networks and relation databases, all kinds of basal information in air transportation system can be shared by controllers, and dynamic information of aircraft and the condition of controllers and pilots can be acquired in real time and stored in the global database. Integrated information about flight safety is extracted, and false instructions and potential dangers are detected using model analysis, on-line analysis & processing, or artificial intelligence, so that alerts and advice are given to controllers in time. The second step is system-integration on the basis of information integration. In this step, the optimal schedule of flow within a whole country or regional area is introduced, and flight safety is ensured at a higher level. Thus profitability can be improved. In information integration, the investment is comparatively small. But it is difficult to deal with many kinds of information (including speech information and radar information, etc.) and the integration of data with different structures.

III. DESIGN OBJECTIVE OF ATCCMS

For safety critical system, the ATCCMS integrates all current ATC information and efficiently deals with basal data including speech information, radar information, and flight plan information so as to monitor actual operation, and to provide ATC departments with good decision-making information.

According to the practice of air transportation systems in China, the design objective of ATCCMS is established as follows.

- Accurately identifying the controller's instructions so as to extract command information.
- Realizing the correlation of command information, radar data and flight plan data.
- Efficiently detecting flight conflict based on radar track information and potential conflict based on control instructions (i.e., pseudo-conflict). The response time of the system is less than two seconds
- Efficient conflict alerting (the percentage of false alerting and missed alerting are less than 5%).
- Providing referenced advice for exceptional cases.
- Efficiently managing basal data (including relation mode and multidimensional mode).
- Recording and analyzing global flight status data and command information.
- Providing comprehensive information query and on-line analysis & processing of flow information.
- Having openness, expansibility and good communication capability.

IV. THE FUNCTION ARCHITECTURE OF ATCCMS

According to investigation, the function architecture of ATCCMS is given in Figure 1, which consists of four primary parts: basal data source, operation-level sub-system, decision-making-level sub-system and supporting environment. In Figure 1, PLN, FPL, and CPL are three telegrams, and denote, in that order, the plan message, field flight plan message, and current flight plan message. The other abbreviations in Figure 1 will be introduced in the following sub-sections.

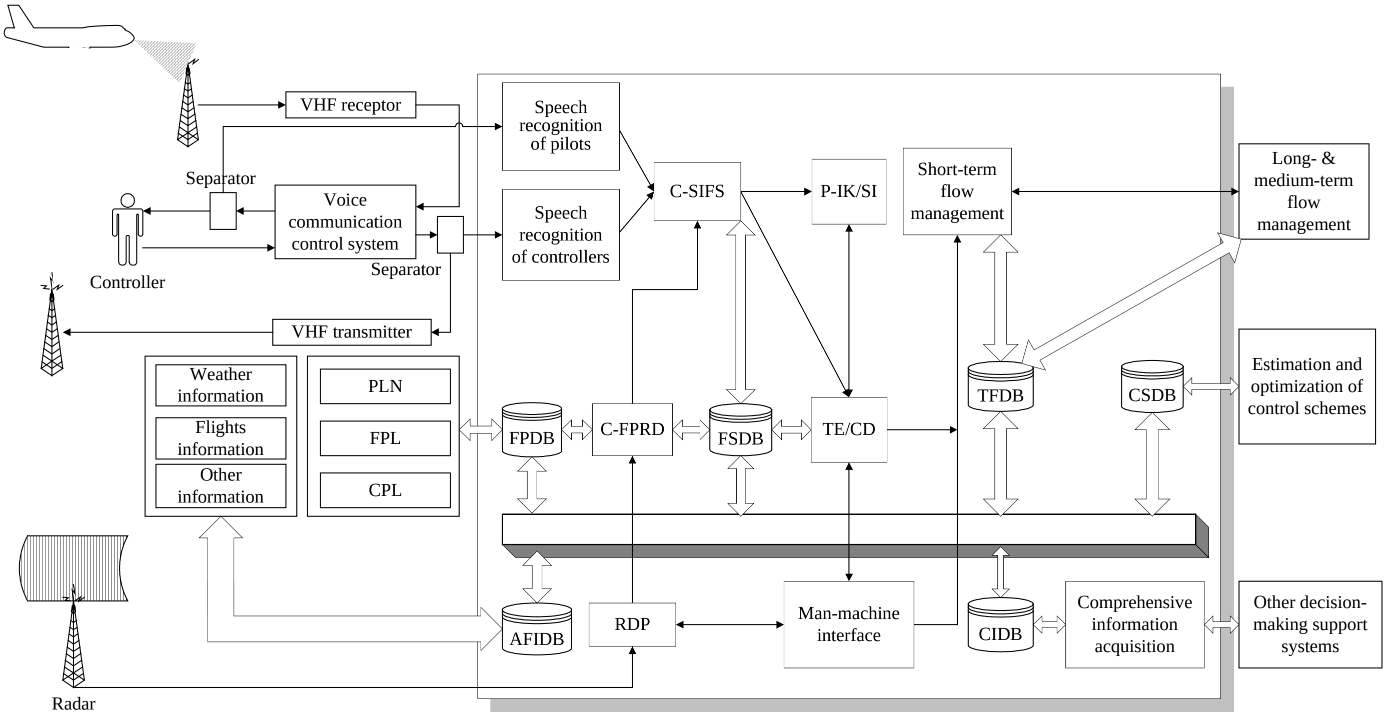

Figure 1. Function architecture of ATCCMS

A. Operation-Level Sub-system

Operation-level sub-system consists of seven modules: speech recognition and speech processing (SR/SP), radar data processing (RDP), correlating flight plan and radar data (C-FPRD), correlating speech information and flight status (C-SIFS), processing intelligent knowledge and special information (P-IK/SI), trajectory estimation and conflict detection (TE/CD), and man-machine interface.

- Speech recognition and speech processing (SR/SP)—This transforms the controller's speech signal into command semantemes. Speech recognition outputs are post-processed so as to extract semantemes. The final results are verified so as to ensure its consistency with the ATC radar data, flight plan and routine. Because of the limited number of controllers, personal voice models for each controller can be established to improve the accuracy recognition rate. Speech recognition of pilots may be regarded as choices of the system.

- Radar data processing (RDP)—After being processed by the fore-terminal processor, the original signal generated from radar is integrated with the Secondary Surveillance Radar (SSR) code and all kinds of flight information (altitude, speed, and heading). With a valid data format, the integrated information is transmitted to the man-machine interface.
- Correlating flight plan and radar data (C-FPRD)—This extracts telegram information such as PLN, FPL and CPL from the flight telegram auto-disposal system, and correlates the Secondary Surveillance Radar (SSR) code and the objects identified by radar, i.e., it adds call signs of scheduled flights to the corresponding item of the radar record.
- Correlating speech information and flight status (C-SIFS)—This, first, extracts important control instructions such as flight numbers and call signs; then it correlates these control instructions and flight status data (the radar data correlated with the flight plan); finally selects a radar trajectory record related to control instructions, and makes preparations for trajectory estimation.
- Processing intelligent knowledge and special information (P-IK/SI)—This processes intelligent knowledge (e.g., expert experience) and some information for exceptional cases.
- TE/CD—According to recognized control instructions and the current flight status, airplane performance, and weather conditions, this estimates a pseudo-trajectory (the possible trajectory after executing the current control instructions) of the airplane, and verifies whether the airplane violates safety separation with a nearby airplane. If a conflict is detected, alert is immediately given to the man-machine interface.
- Man-machine interface—This gives the same display as a radar graphical interface to controllers. When there is a pseudo-trajectory, it is displayed on a screen. When a coming conflict is detected, it is displayed. At the same time the conflict objects and their conflict time and conflict probability are highlighted and an alarm sounds. Furthermore, the input and output of decision-making-level sub-systems are integrated into the man-machine interface.

B. Decision-Making-Level Subsystem

The decision-making-level sub-system is not real-time. It mainly provides the command director, flow administrators and other principals of the ATC department with high-level decision-making support. It mainly includes following two parts.

- Short-term traffic flow management—According to the flight plan, radar data, and controller-pilot communications, this dynamically monitors air traffic flow and stores this flow in the flow database. Using experience models and optimization models, it gives the flow control scheme for a two to three hour time frame.
- Comprehensive information acquisition—According to decision-maker's requirements for all kinds of integrated information for ATC, this flexibly extracts basal data from the database and establishes a multidimensional data model so as to create integrated information immediately.

C. Data Interface

Data input in ATCCMS includes two parts. One is basal data such as radio (VHF and HF) speech signal, flight telegram, radar signal, and other auxiliary flight information (e.g., weather and navigation information). The other is data coming from upper levels such as long- and medium-term flow management information, and evaluation and optimization information of the control scheme. The output device is mainly a wide-screen graphical display.

D. Supporting Environment

The supporting environment, which is very important for information integration, includes a computer network and database environment. The computer network ensures the sharing of information and data for all users involved in ATC. The database environment consists of an auxiliary flight information database (AFIDB), a flight plan database (FPDB), a flight status database (FSDB), a traffic flow database (TFDB), and a comprehensive information database (CIDB).

V. LOGIC ARCHITECTURE OF ATCCMS

For programming convenience, the modularization logic architecture of ATCCMS is presented as Figure 2. The network communication interface and voice communication interface are on the lowest level. The voice communication between controllers and pilots is input through an appropriative interface, and other basal information is input through high-speed LAN or a special telephone line. The database management system is at the top of the lowest level. This module, on the one hand, receives and stores the data coming from the network communication interface. On the other hand, it serves the query of the upper module. The radar data processing (RDP) module judges the radar data format and creates images. The flight plan data processing (FDP) module extracts all kinds of flight plan data from the flight telegram automatic disposal system and stores them in a database, from which the controller can make a query. After it is input into the system, voice communication between controllers and pilots is first enhanced and processed by limiting noise, and then post-processed by a natural language processing module to ensure the rationality of semantic information.

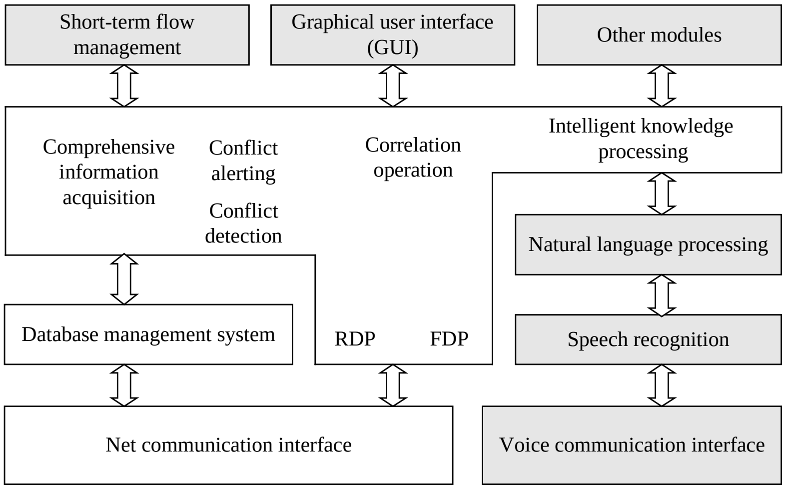

Figure 2. Logic architecture of ATCCMS

Multi-step correlation operation is the kernel of ATCCMS. In the first step, flight plan data and processed radar data are correlated. In the second step, the information extracted from the speech recognition and post-processing module is first processed by intelligent knowledge; then reverted to control instruction semantemes; and finally correlated with radar data and flight plans. In the third step, the conflict detection module checks the future flight trajectory and pseudo-trajectory. If a conflict is found, the controller must be alerted.

The short-term flow management module can ensure high-level flight safety through optimizing the flow within a short period. The graphical user interface (GUI) module and short-term management module both exchange substantive data with the lower layer module, as shown in Figure 3.

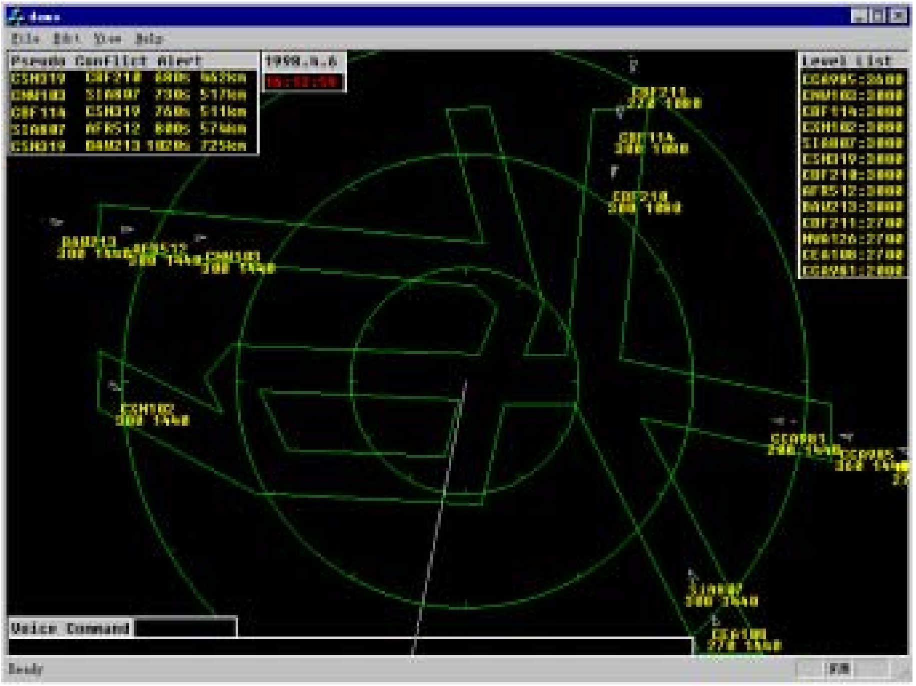

Figure 3. Conflict detection and alerting GUI of ATCCMS

VI. ANALYSIS AND EXPERIMENT ON KEY COMPONENTS OF ATCCMS

The key components of ATCCMS include: (1) the speech recognition and post-processing of control instructions; (2) the realization of flight conflict detection and an alerting algorithm; (3) modeling short-term air traffic flow management; (4) the development and realization of a global flight status database; (5) the analysis and development of a real time system. Among these, (1) and (2) are the most important parts for the success of system. The following sub-sections will discuss these two parts.

A. The Speech Recognition and Post-Processing of Control instructions

Taken as a limited set, controller instructions in air traffic control have the following characteristics: (1) the grammar structure is determinate, concise and has no other possible meanings; (2) the vocabulary is limited. The common vocabulary is not more than 200 words. Even including the flight call signs and other special vocabulary, there are no more than 1000 words; (3) the speech speed, 100 words per minute, is constant; (4) there are few voice models of controllers because of the limited number of controllers; (5) International Standard English is the conversation language. So the main tasks of recognition of control instructions are focused on: choosing the right speech recognition engine and hardware & software platform, modeling the controller's voice and vocabulary library, and compiling grammar files [6].

Maintaining accuracy rates is a significant challenge in developing speech recognition applications. Two key issues exist when considering accuracy rates; first, the precision rates must be within acceptable levels for the particular system. Additionally error-handling measures are necessary as these systems are not perfect and some errors will occur. Error levels vary with each system's purpose. Safety critical systems, such as ATC communications and others involving sensitive data require the highest degree of accuracy possible which should be decided upon during the system's design phase. In addition, it is also necessary to decide what type of errors is preferred. In the recognition process, the speech recognition system can attempt to eliminate possible results that it deems incorrect.

According to the complexity of grammar structure, three samples were made to test the recognition effects of control instructions. For each sample, eight group experiments were made. All experiments were run on an Intel Pentium Pro166MHz CPU, 64M Memory, Creative SB16 sound blaster card, MS-Windows 95. The speech recognition engine was an IBM VoiceType V3.1. The results for accuracy recognition rates based on words are shown in Table I. The results for recognition error classified by error type are shown in Table II.

TABLE I RESULTS FOR ACCURACY RECOGNITION RATE BASED ON WORDS

Sample	Grammar complexity	Vocabulary	Lowest accuracy recognition rate (%)	Average accuracy recognition rate (%)
Sample 1	Simple	853	98.1	98.8
Sample 2	Medium	1,192	92.9	95.7
Sample 3	High	2,425	88.8	95.5

TABLE II RESULTS FOR RECOGNITION ERROR CLASSIFIED BY ERROR TYPE

Error type	Sample 1	Sample 2	Sample 3	Total
Adding numeral error	3	1	6	10
Recognizing numeral error	0	5	6	11
Adding word error	0	1	2	3
Recognizing word error	2	3	6	11
Missing word	1	2	1	4
Recognizing short-sentence error	0	3	1	4
Unrecognizing whole-sentence	0	2	9	11
Speaking error	0	1	0	1
Total number of recognition error	6	18	31	55
Total number of sentences used in Experiment	72	137	204	413

These results in Table I show that the average accuracy recognition rate based on words is more than 95%. The results in Table II show that, if it assumed that each sentence of control instructions corresponds to one group of semantic data, the accuracy recognition rate based on semantemes is decreased to 86.7% ((413-55)/413=86.7%). In ATCCMS, the object of taking speech recognition techniques is to extract the semantemes of control instructions that can change the flying status of an aircraft, rather than to simply convert speech into words. So, three level error-processing mechanisms were developed to post-process the results of speech recognition, which can ensure accuracy in extracting the semantemes of key control instruction.

1) Level 1, processing ATC knowledge.

For each ATC unit, there are some data and procedures involved in its control area. From these data and procedures, a set of intelligent rules and reasoning mechanisms can be made so as to form an ATC knowledge library. At this level, the knowledge in ATC knowledge library is used to verify the validity of results of speech recognition. If some determinate errors are found, they can be revised automatically.

2) Level 2, processing information correlated radar data.

Because of the validity of most information involved in control communications can be verified through checking the real time radar data, at this level, based on radar data, the variance between the results of speech recognition and radar data can be corrected and renewed.

3) Level 3, processing man-machine interaction.

If some sentences cannot be recognized through level 1 and level 2, or are missed because of disturbance of environment noise, level 3 is needed to confirm these sentences by man-machine interaction.

So, the recognition errors in Table II are classified as follows: (1) light errors involved in the missing of prepositions and some simple adjectives; (2) errors that can be corrected in level 1; (3) errors that can be corrected in level 2; (4) severe errors that miss much information and only can be corrected in level 3. The results for recognition error of these classes are shown in Table III.

TABLE III RESULTS FOR RECOGNITION ERROR

Error class	Sample 1	Sample 2	Sample 3	Total	Percentage
Class 1	1	1	4	6	10.9%
Class 2	0	8	13	21	38.2%
Class 3	5	3	8	16	29.1%
Class 4	0	6	6	12	21.8%
Total	6	18	31	55	100%

The results in Table III show that the errors in class 1, class 2, and class 3, which account for 78.2% of all errors, can be corrected automatically in post-processing. This states that, after three levels post-process, the validity and reliability of the semantemes of control instructions are greatly improved.

B. Flight Conflict Detection and Alerting

This component consists of modeling aircraft motion, predicting aircraft trajectory, and detecting conflict and alerting. To model aircraft motion, according to the particle motion equation, vertical motion and horizontal motion are modeled [7]. The usual algorithms for predicting aircraft trajectory are simple extrapolation: the least square extrapolation, the $\alpha - \beta$ filter, and the Kalman filter [8]. Of these, the Kalman filter is the best. Because most flight conflict occurs within the approach control area, the algorithm for conflict detection must have the ability to detect three-dimensional conflict, and must satisfy the real-time requirement of systems [9] and [10]. According to the logic of TCAS, ATCCMS must reduce the alerting errors (including alerting for conflicts that should not be alerted for, and missing conflicts that should be alerted for) as completely as possible [11].

The objective of conflict detection and alerting is to evaluate a set of planned or predicted trajectories on their conflict potential and to supply other ATC sub-systems with the conflict information. A number of approaches have been proposed to automate air traffic conflict detection and resolution (CDR) [12]. In theory, the conflict detection approaches include the deterministic approach and the probabilistic approach [13]-[15].

The deterministic approach, the classical geometric conflict prediction approach, was performed on a pair of predicted 4D trajectories. Input for the deterministic conflict detection is the predicted 4D trajectory. The uncertainty of the predicted 4D trajectory is translated into areas around the predicted trajectory. These areas can be referred to as protection zones. The size and shape of the protection zones may vary with time. The protection zones for the horizontal plane and for the vertical plane are defined independently. Horizontal and vertical distances between protection zones should meet safety requirements. Two aircraft are said to be in conflict when the distance between the protection zones of those aircraft becomes smaller than the minimum allowed distance between them.

The probabilistic approach aims to predict the probability that the separation between two predicted flights falls below a certain separation threshold. This probability is called conflict probability. The goal is to keep the conflict probability below some acceptable level (alert threshold).

The deterministic model and the probabilistic model of conflict detection applied in earlier ATCCMS can be found in [17]-[20]. Table IV gives results for deterministic and probabilistic algorithms on the practical data of Beijing ATC on May 1, 2001, from 8:00 to 20:00.

Table IV shows that the alert number of the deterministic algorithm is more than that of the probabilistic algorithm. According to field observation, there are many alerting errors in the deterministic algorithm, which can be filtered by the probabilistic algorithm. As the alert threshold increases, the capability of the probabilistic algorithm to filter the alerting error of the deterministic algorithm becomes more remarkable.

TABLE IV RESULTS FOR DETERMINISTIC AND PROBABILISTIC ALGORITHM

No.	Time	Deterministic algorithm (Alert number)	Probabilistic algorithm			
			Alert threshold: 0.85		Alert threshold: 0.95	
			Alert number	Filtering rate (%)	Alert number	Filtering rate (%)
1	08:00-10:00	44	27	38.6	23	47.7
2	10:00-12:00	45	24	46.7	21	53.3
3	12:00-14:00	19	8	57.9	7	63.2
4	14:00-16:00	20	10	50.0	8	60.0
5	16:00-18:00	48	29	39.6	23	52.1
6	18:00-20:00	20	10	50.0	8	60.0
	Total	196	108	44.9	90	54.1

However, for the probabilistic algorithm, there are still some alerting errors that cannot be filtered. Sometimes, the duration of the alert is very short, i.e., a transient alerting was given so that controller was confused by it. Analysis for these phenomena was given in [21] and [22], in which an improved conflict detection algorithm was also introduced. The improved algorithm, which integrates the ATC procedures, continuously detects the conflicts in certain time periods. Three important parameters are needed in the improved algorithm: alert threshold, the probability threshold of continuous detection, and continuous detection times. For each time of continuous detection, if the other two parameters are satisfied, conflicts will be detected. Figure 4 shows the flow chart of the improved algorithm. Table V gives the comparison of deterministic, probabilistic, and improved algorithms.

TABLE V COMPARISON OF DETERMINISTIC, PROBABILISTIC, AND IMPROVED ALGORITHMS

No.	Time	Deterministic algorithm (Alert number)	Probabilistic algorithm (Alert threshold: 0.85)		Improved algorithm	
			Alert number	Filtering rate (%)	Alert number	Filtering rate (%)
1	08:00-10:00	44	27	38.6	7	84.1
2	10:00-12:00	45	24	46.7	7	84.4
3	12:00-14:00	19	8	57.9	4	78.9
4	14:00-16:00	20	10	50.0	3	85.0
5	16:00-18:00	48	29	39.6	10	79.2
6	18:00-20:00	20	10	50.0	3	85.0
	Total	196	108	44.9	34	82.7

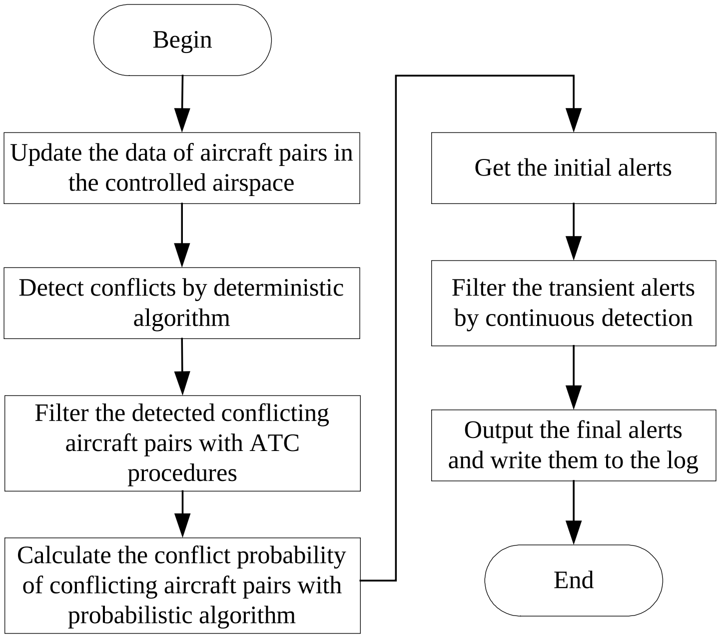

Figure 4. Flow chart of the improved algorithm

The results in Table V show that the improved conflict detection algorithm is more effective than the deterministic and probabilistic algorithms. It can reduce the number of alerts to a reasonable range. The improved algorithm is applied in the current version of ATCCMS. The system can detect conflicts and pseudo-conflicts caused by control instruction error in 20 minutes at most, and present five pairs of conflicted aircraft in their time order (Figure 3). After the controller solves these conflicts, the alert stops. The system response time is not more than 2 seconds.

VII. CONCLUSIONS

ATCCMS, developed with Visual C++ 6.0, integrates radar information, flight plan information, speech information of control instructions, and weather information into a common platform. Its function architecture and logic architecture were discussed in this paper. It can ensure reliable safety through monitoring the whole process of controller's instruction.

In ATCCMS, multi-item unit techniques are used, such as speech recognition and its post-processing, flight conflict detection and alerting, and short-term flow management. These units monitor the different parts of the ATC command process, and support and reinforce each other by information integration. The simulation results show that the information integration technique is more effective than simply improving unit technique, and it can be a new promising method for solving the control and optimization problem of a large, complex system. ATCCMS can present, besides system safety, an information environment for air traffic control automation and the national flow management system of China.

However, the speech recognition component of ATCCMS currently relies on a Verbex voice recognition card, which is only supported by DOS drivers and is not supported by the Windows platform. Verbex also required users to train for up to one hour before using the program. While this ensured higher accuracy rates, the training period was inconvenient and required considerable time and effort in maintaining user's voice profiles. At the same time, the ability to use dynamic call signs and complex multi-instruction messages are strongly desired by air traffic controllers. It became clear that the Verbex system needed to be updated.

The direction for future work is to develop a new speech recognition system that can work well with Windows-based applications and support large complex grammar files. The grammar files could be easily modified to allow for multiple pronunciations of a single word or phrase. Most importantly, for the new system, user's training time should be eliminated and allow users with discrete accents to readily use the application.

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