Modelling and simulation of cognitive processes in air-traffic control based on mutual beliefs

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Abstract. Shared situational awareness among air-traffic controllers (ATCOs) and pilots is essential for airport safety. This paper presents models and simulations of cognitive activities that underlie the communications between ATCOs and pilots. This model facilitates the shared situational awareness analysis and can produce quantitative data to inform the design of communications protocols. A simulation using data from the official 1977-Tenerife-accident report, which reveals the cognitive processes that could explain the communications and behavior detailed in the report, suggests alternate explanations. This proof-of-concept test suggests that the proposed model and simulations can be used for analyzing air-traffic control accidents at airports.

Keywords: Mutual belief, Accident analysis support, Agent-based simulation

1. Introduction

In recent years, the demand for air transport has grown rapidly. At the Haneda Tokyo International Airport, one of the largest airports in the world, for example, the number of arrival and departure slots during daytime hours have been expanded, and in peak periods, aircraft take-off and land once every two minutes. To ensure safety under these circumstances, the role of air-traffic controllers (ATCOs) has become increasingly important. ATCOs working at control towers and control centers monitor the status of aircraft around the airport visually or by a radar screen and communicate constantly with pilots. For example, ATCOs monitor aircraft movements from the control tower with binoculars. In addition, ATCOs give instructions to pilots by radio. Because miscommunications can lead to serious accidents, mutual understanding and shared situation awareness (SA) among ATCOs and pilots is essential for safe ground control operations.
Conventional safety engineering is intended to keep the number of undesirable outcomes as low as possible. Further, engineers tend to believe that safety can be realized by removing actual and possible causes for undesirable outcomes, in the so-called Safety-I conception. In contrast, to respond to the increasing complexity of socio-technical systems like air-traffic control systems, the recently developed Safety-II framework [1, 2] emerged to stress the importance of successful operations in tandem with avoiding undesirable outcomes. In addition to existing accident investigation methods, the implementation of Safety-II for air-traffic control operations needs a method for analyzing the cognitive processes behind the behavior that led to an accident. This analysis can be used to optimize communications protocols to both ensure safety and improve operational performance. The strict operationalization of communications and cognitive processes is needed for such an analysis.

Many theoretical and empirical studies have addressed human cognitive activity. SA, in particular, has been a focus of studies of the behaviors and mental processes involved in effective team cooperation [3-5]. However, most such studies do not focus on the cognitive processes involved in building and sharing SA, but instead only consider SA as an outcome of perception. Few studies have considered both aspects of SA. Blom and Sharanskykh’s work on the formalization of the cognitive processes behind shared SA is one such example, in which they proposed a formalization of the cognitive process underlying team communication that uses a mathematical model of relations between agents. This formalization was then applied to the description of communications leading up to an aviation accident [6]. While this framework provides systematic formalization and symbols that represent mental contents and physical actions like an agent’s SA, an agent’s SA about other agents, and communication between agents, the framework does not clearly distinguish between these three layers of mutual beliefs, nor does it consider inter-layer interactions [7]. A more-detailed description of cognition and communication that considers these aspects of mutual beliefs may offer deeper insight into the dynamics involved in air-traffic control.

The cognitive behavior involved in team cooperation has also been modeled successfully with computer simulations. In recent years, various simulations have been used to better understand aviation communications. Furuta et al. [8] used agent-based simulations to assess the options for the redesign of ground-aircraft operations at Haneda Airport. Karikawa et al. [9] developed a cognitive-systems simulation of en-route control using cognitive task analysis and identified relevant features of the control strategy. However, like human-factor studies on SA, few of these studies have considered both team cognition processes and mental contents. Furuta et al. [10] developed a computer simulation using a cognitive model of team cooperation for en-route air-traffic control [11] based on ethnographic field observations that incorporated the concept of mutual belief. However, since the purpose of this simulation was to replicate specific scenarios selected from the field observations, the resulting model is case-specific and cannot be generalized for the detailed analysis of cognitive processes.
Therefore, a novel psychological model and operationalization of the relevant psychological processes is needed to achieve generalizability and comprehensiveness.

This paper makes the following three contributions: the cognitive processes involved in ground control communications between ATCOs and pilots is operationalized with three layers of mutual beliefs, ground control operations are simulated using an agent-based cognitive model that incorporates this three-layer structure, and team cognition processes are replicated using the simulation.

The rest of the paper is organized as follows. In the next section, the methods for modeling an airport and the cognitive states and processes of the ATCOs and pilots are explained. Section 3 describes the simulation we developed to provide the set of possible explanations of the cognitive processes that lead to observable actions in ground control operations. The simulation is then run with data from an actual accident to demonstrate its usefulness with a case study, and the simulation outputs are shown to agree well with observed behavior in Section 4. Finally, conclusions are drawn in Section 5.

2. Models and psychological constructs

The agents we consider in this study are ATCOs and aircraft pilots. These agents must cooperate to coordinate ground traffic on an airport’s runways. This section describes how the airport and agents are modeled in our analysis.

2.1. Airport model

The airport model represents relevant environmental conditions including the runway configuration and visibility. Fig. 1 shows a schematic of the model.

The configuration of the airport is represented as a directed graph; nodes represent intersections and edges represent runways and taxiways. The labeled edges include information about the road type, road state, and the presence of aircraft. Roads are divided into three types: runways, taxiways parallel to the runway (e.g., taxiway H in Fig. 1), and taxiways connecting the runway and taxiway. The road state is described as the availability of the road and presence of aircraft. The availability of the road determines possible taxiing route.

Visibility is the maximum distance at which an object can be clearly discerned with the naked eye. Quantitative visibility data measured by instruments are available at actual airports; however, for the sake of simplicity in our computer simulations, the visibility is modeled at either good or bad. In the simulation, visibility influences whether agents can see information in the environment.
2.2. Team cognition model for ATCOs and pilots

The team cognition model [7, 12] is used to represent the mental states of the ATCOs and pilots. This subsection firstly outlines the basic model, and then explains the structure of team cognition in ground control operations, the operationalization of psychological constructs, and the representation of cognitive processes and interactions.

2.2.1. Team cognitive model

Kanno et al. [7] proposed a model of cognition in two-person teams based on the concept of mutual belief. Mahardika et al. [12] extended this model to describe team cognition among more than two agents by introducing the concepts of mental subdivision and subgrouping. The key concept in explaining team cognition is the mutual beliefs that describe a person’s beliefs about the other team members’ cognition and beliefs that are hierarchically justifiable. Mutual beliefs can theoretically be held ad infinitum, but in practice, two or three layers of cognition are sufficient for representing the psychological states of team members. Therefore, for a two-agent team of agents A and B, the model includes the following three layers:

- **Ma/Mb** (top layer): A/B’s cognition (all individual cognition except for beliefs)
- **Ma’/Mb’** (middle layer): A/B’s belief about Mb/Ma (belief about the other member’s cognition)
- **Ma”/Mb”** (bottom layer): A/B’s belief about Mb’/Ma’ (belief about the other member’s belief about the team’s mental state)

An advantage of introducing mutual beliefs in an agent-based model of this situation is that the model can distinguish between the mental contents that are really shared among team members (Ma∧Mb) and the content that is only believed to be shared (Ma∧Ma’). The latter shared content is an awareness of the shared situation held in each member’s mind, which can describe cognitive processes behind the
interactions within team. For example, if inconsistency or insufficient shared belief is present in the first and second layers of belief, the analysis will return a motive for communication and interaction to correct the inconsistency or increase shared beliefs.

Mental subdivision and subgrouping is another key concept in describing team cognition. Mental subdivision is deduced theoretically from the team cognition model of a dyadic case. If the number of team members increases, the number of beliefs about other members will also increase. In the case of a team with n members, the middle layer of mutual beliefs can be divided into n − 1 subdivisions and the bottom layer can be divided into (n − 1)² subdivisions. However, people are unlikely to hold all n − 1 and (n − 1)² beliefs, rather, the mind usually chunks them into 2 to 5 subgroups. This chunking function is known as mental subgrouping.

2.2.2. Belief structure of agents involved in ground control operations

Below, the Tenerife airport accident [13] serves as a case study for simulations and analysis with the team cognition model. The case study is modeled with three agents, including one ATCO and two pilots. Each agent’s cognition is represented with the three-layered team cognitive model with several mental subdivisions, as shown in Fig. 2. Because aircraft pilots communicate only with the ATCO and act in response to instructions from the ATCO, beliefs about the ATCO’s cognition are much more motivating to the aircraft pilot than beliefs about other aircraft pilots’ mental states. Therefore, the subdivision of the aircraft pilot’s beliefs about other aircraft pilots’ cognition is excluded in the context of ground control. On the other hand, because the ATCO needs to be confident that their air-traffic control plan is truly understood by all relevant pilots, the ATCO needs to attend to all the pilots’ mental states. Therefore, mental subgrouping is not applied to the ATCO’s beliefs about pilots. In each layer of mutual belief in Fig. 2, the set of beliefs (2.2.3) is represented by M, M’, or M”. For the mutual belief layers of pilot A in Fig. 2, M(A), M’(A,ATCO), and M”(A,ATCO,A) represent mental contents about A’s cognition, A’s belief about ATCO’s cognition, and A’s belief about ATCO’s belief about A’s cognition, respectively.

Figure 2: Cognitive models of an ATCO and pilots.
2.2.3. Mental contents

When a team collaborates to achieve a specific common goal, the perception of each team member, including information about other members, is essential to generating the appropriate SA. Endsley [14] defined SA as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.” Each agent’s SA grounds decision making in aviation contexts. The information needed so that pilots and ATCOs can have sufficient SA has been subjected to goal-directed task analysis, in which major goals, subgoals, decisions, and the associated SA are elicited from experiences pilots and ATCOs [15, 16].

In each layer of the team cognition model, beliefs are represented as mental contents. Mental contents and the conditions around them can motivate communication, and beliefs can be transferred to other agents by verbal and non-verbal communication. We extracted mental contents of the SAs of the ATCO and pilots involved in the Tenerife airport accident from the communication logs included with the accident report [13], and these mental contents are operationalized in our model as shown in Table 1, where A stands for agent A, and X and Y are the names of the terminal edges corresponding to the runway and taxiway. For example, if an agent holds a mental content of “position(A,X)” in his first and second layers, this means that the agent is aware that the position of agent A is X and believes that his teammate is also aware that agent A is now at X. Each agent’s SA at each point in time is represented as a set of mental contents that take values such as true/false, indeterminate, or a geographical position.
### Table 1: Mental contents and operationalization

| Mental Construct                  | Example                                                                 |
|----------------------------------|-------------------------------------------------------------------------|
| Contact with tower               | `sameFrequency(A, true or false)`                                      |
|                                  | This mental construct describes whether the pilot A holds a frequency that can communicate with ATCO or not. |
| Position                         | `position(A, unknown or X)`                                           |
|                                  | This mental construct describes the position of pilot A.               |
| On runway                        | `onRunway(A, true or false)`                                          |
|                                  | This mental construct describes whether pilot A is on the runway or not.|
| Taxi clearance                   | `taxi_clearance(A, X,Y,…, or unknown)`                                 |
|                                  | This mental construct describes the route to taxi.                     |
| Lineup & wait clearance          | `L&W_clearance(A, true,false,or unknown)`                              |
|                                  | This mental construct describes the status of clearance to line up and wait on runway. |
| Air traffic control clearance    | `ATC_clearance(A, true, false, or unknown)`                            |
|                                  | This mental construct describes the status of ATC clearance before takeoff. |
| Takeoff clearance                | `takeoff_clearance(A, true, false, or unknown)`                        |
|                                  | This mental construct describes the status of takeoff clearance.        |
| Report point                     | `reportPoint(A, onRunway, true or false)`                              |
|                                  | This mental construct describes the condition for pilot A to report its position to ATCO. |
| Availability of the road         | `isAvailable(X, true, false, or unknown)`                              |
|                                  | This mental construct describes the status of road X.                  |

#### 2.2.4. Inference process

Inference is modeled as processes of updating the status of mental contents in a serial manner. This process is triggered when new information enters each layer by communication or perception of the environment. This updating process is illustrated in Table 2. Mental contents can be updated in two ways. A serial update occurs within a single layer and is based on prescribed rules derived from the airport model and aviation regulations. Four rules are derived from the configuration of the airport model. For example, when the mental content of aircraft A’s position is updated to runway X, the status of the mental content representing the availa-
bility of runway X is changed to express that it is not available to other aircraft. On the other hand, seven rules are derived from aviation regulations. For example, when the mental content of aircraft A’s position is updated to runway X, the mental content expressing A’s reporting point is updated to the status that A should report to the ATCO when leaving the runway. The other types of mental content updates occur between layers of an agent’s own mutual beliefs: complement and assumption. Complement processes copy a mental content in the middle layer to the top or bottom layer. It occurs when the status of a mental content is not identical between the layers and the agent believes that other agents know the correct state of affairs. Assumption processes copy the mental content in the top layer to the middle or bottom layer. This process occurs when the state of affairs represented in the agent’s top layer is not identical between the layers and the agent believes that his or her teammates know the true state of affairs. Agents do not make any error in copying a mental content with different status from the original layer when these processes occur. In the simulation model, both process occur only after perception and communication but in a real-world situation, they may happen at any time.
Table 2: Inference processes included in the model

| Process       | Function                                                                 |
|---------------|--------------------------------------------------------------------------|
| Think/Believe | Update mental construct within a layer. e.g. When aircraft A is at runway X, it believes that that aircraft A is on the runway. |

- Complement: Agent copies the mental construct in the middle layer to the top/bottom layer.

- Assumption: Agent copies the mental construct in the top layer to the middle/bottom layer.

2.2.5. Interactions

In interactions, the status of a mental content is updated by perception (interactions with the environment) or communication (interaction with other agents). The types and operationalizations of these interactions are listed in Table 3. The format for representing an interaction includes the type, subject agent of the interaction, object agent (if one exists), and the target of the mental content.

Perception updates agents’ information about the environment. However, this interaction is impeded when visibility is poor.

Communication is intended by an agent when certain conditions occur. There are two types of triggers for communication in our model. First trigger is the communication regulations for radio contact. For example, when a message has been transmitted, the receiver needs to acknowledge the message by repeating it back. The second trigger is a mismatch of the statuses represented in one’s mutual beliefs. For example, when there is a discrepancy be-
tween an agent’s mental state and one’s belief about other member’s mental state, the agent can feel motivated to request, confirm, or inform to resolve the discrepancy. The “Request” interaction is selected if the content of the mental content is unknown. “Confirm” is selected when one agent thinks the other agent knows the correct information about a certain mental content and the status of the agent’s cognition and its belief is mismatched. “Inform” is selected when an agent knows the correct state of a certain mental content and the state of affairs is mismatched between the agent’s. Agents do not make any misstatements nor do they mishear any communication, but they may miss a remark.

Table 3: List of interactions

| Interaction  | With     | Example                                      |
|--------------|----------|----------------------------------------------|
| Percept      | Environment | per(A, position(A, X))                        |
|              |          | Agent A percepts that agent A is at position X. |
| Request      | Others   | req(B, A, position(A, unknown))              |
|              |          | Agent B request agent A to inform agent A’s position. |
| Confirm      | Others   | conf(B, A, position(B, X))                   |
|              |          | Agent B confirms agent A that agent B’s position is edge X. |
| Inform       | Others   | inf(A, B, position(A, X))                    |
|              |          | Agent A informs agent B that agent A’s position is edge X. |
| Acknowledge  | Others   | ack(B, A, position(A, X))                    |
|              |          | Agent B acknowledge to agent A that agent A’s position is edge X. |

3. Simulation

This section explains the simulation of team cognition behind actions that can be observed in ground control operations that implements the models of the cognitive states of the ATCO and pilots introduced above. The architecture of the simulation is illustrated in Fig. 3. The data input to the simulation are the environmental conditions of the target airport and the communication log between ATCOs and pilots. Data extracted from the report about the Tenerife airport accident in 1977 were used as the input data for the following simulation, how-
ever, other data such as communication logs from normal operations at any airport or virtual scenarios can also be input to the simulation. The outputs of the simulation are 1) communication and cognitive processes of each agent and 2) shared SA calculated from the cognitive status of each agent at each timestep. The details of these outputs are explained in the following subsections.

The simulation flow is shown in Fig. 4. The time between one communication and the next is defined as one timestep. At each timestep, first, communication data are input. Second, all agents look at the environment and perceive any available information about nearby taxiways or runways, according to visibility conditions at the agent’s current position. Third, mental contents are updated based on the inference processes explained in the previous section. Fourth, all possible communications in the next timestep are listed considering the radio communication regulations and conditions of the three-layer mental contents. Last, by comparing these possible communications with actual communication that was logged in the next timestep, possible communications and cognitive processes that contradict with the actual communication are excluded from the next simulation steps.

![Simulation architecture](image)

Figure 3: Simulation architecture.
3.1. Output table

To allow easy understanding and detailed analysis of the processes of communication and cognition in ground control operations, an output table was developed for describing and organizing the simulation results in chronological order. The organization of the output table is shown in Fig. 5.

The first column shows the timestep of the simulation output. The second column shows the observations conducted by the three agents. At timestep 20, KLM perceived the environment and recognized that its position was at edge 14. The third column shows the input content of verbal communication described in Table 3 along with the intended reason for that communication derived from the cognitive status at the previous timestep. At timestep 20, ATCO requested KLM’s position because KLM’s position was unknown. At timestep 21, KLM informed ATCO of its position because it was requested in the previous timestep. Later columns show the cognitive processes of each agent. Mental contents that are updated from observation or communication are listed along with the reason for the update. Mental contents that are recorded after the arrows were updated based on the previous mental content. For example, at timestep 20, since the position of KLM was requested by the ATCO, KLM believes that the ATCO does not know KLM’s position at this point. Also, KLM recognizes in its top layer that its position is at edge 14, from its observation, and further recognizes that it does not know the status of the line up. These mental states motivate agent KLM to wait for
| Time | Observation | Reason | Communication | Reason | KLM’s process | Reason | ATCC’s process | Reason | PA’s process |
|------|-------------|--------|---------------|--------|---------------|--------|----------------|--------|--------------|
| 20   | unkno req(ATC,KLM, position(KLM,unknown)) | req | KLM-ATC: position(KLM,unknown) | ASS    | KLM: position(KLM,14) == > KLM: L&W clearance(KLM,unknown) | ASS    | KLM-ATC: position(KLM,unknown) | ASS    | KLM-ATC: position(KLM,unknown) |
| 21   | req-INF inf(KLM,ATC, position(KLM,14)) | PER  | KLM: position(KLM,14) | INF    | KLM-ATC: position(KLM,14) | INF    | ATC: position(KLM,14) == > ATC: L&W clearance(KLM,true) == > ATC: isAvailable(14,false) | INF    | PA-ATC: position(KLM,unknown) |

Figure 5: Output table.
3.2. Criteria of shared situation awareness

In addition to cognitive processes behind ground control operations, shared SA was assessed as the cognitive product. As an evaluation criterion for shared SA, completeness as proposed by Shu and Furuta [17] was used. Completeness is the degree to which the agents’ beliefs match the actual situation at hand. We adopted completeness as a criterion because the comprehensiveness of beliefs about team members’ cognition is important for safe ground control, in addition to the degree of agreement between agents. For the team of agents A and B, the completeness of agent B’s belief about agent A’s cognition is assessed as follows:

\[
\text{Completeness of } M'(B,A) = \frac{\text{number of elements in } (M(A) \cap M'(B,A))}{\text{number of elements in } M(A)} \tag{1}
\]

In Eq. (1), M(A) stands for agent A’s cognition and M'(B,A) stands for agent B’s belief about agent A’s cognition. In the context of one ATCO and two aircraft pilots, the completeness of four shared SAs need to be considered: the completeness of aircraft pilot A’s belief about the ATCO’s cognition, completeness of aircraft pilot B’s belief about the ATCO’s cognition, completeness of the ATCO’s belief about aircraft pilot A’s cognition, and completeness of the ATCO’s belief about aircraft pilot B’s cognition.

4. Case Study

To demonstrate how the simulation is used for the analysis of cognitive processes behind team cooperation, communications during an actual airport accident were analyzed.

4.1. Case example: Tenerife airport accident

The Tenerife airport accident occurred in 1977. In this accident, KLM flight 4805 and Pan Am flight 1736 collided on the runway of Tenerife airport and 583 passengers died. The configuration of the Tenerife airport at the time of the accident is shown in Fig. 6 (left). On the day of the accident, both aircraft were waiting for takeoff. The KLM aircraft taxied down the runway first and prepared for takeoff. The Pan Am aircraft was also taxiing on the runway, following the KLM aircraft. The Pan Am aircraft was instructed to leave the runway on the C3 taxiway, but passed C3 and headed for the C4 taxiway. At that time, the KLM aircraft started to takeoff without clearance from the ATCO, having only received ATC clearance for its altitude and direction after takeoff. Though the Pan Am aircraft was still running on the runway, the KLM crew failed to notice the situation and did not cancel the takeoff, so the aircraft collided near the C4 taxiway. The accident report concluded that the main cause of the accident was that the Pan Am aircraft passed exit C3 when taxiing on the runway, despite be-
ing instructed to exit the runway at C3. The report also suggested that the miscommunication about takeoff clearance between the ATCO and the KLM pilot contributed to the accident.

4.2. Simulation models

In the simulation, each aircraft is represented as a single agent. The agents are regarded as a team consisting, as shown in Fig. 2, of the ATCO, KLM 4805, and Pan Am 1736. Let the agent names be ATCO, KLM, and PA, respectively. The log of the communications between the pilots and ATCO in the accident investigation report [13] was used as input data for the simulation. Table 4 shows an excerpt of the communications. In this case, the communication begins between ATCO and KLM and PA joined the radio communication at timestep 13. 34 communications from the log were input to the simulation of this accident.

Figure 6 shows the configuration of the airport and its simulation model represented as a directed graph. Because only the takeoff operation was included in the case study, the graph edges for landing are excluded from the model for the sake of simplicity. According to the report, the horizontal visibility decreased to 300–500 meters from 2–3 kilometers in the middle of the operating period. Therefore, the visibility is set as “good” until the 19th communication and is then changed to “bad.”

![Figure 6: Airport model for the Tenerife accident case.](image)
Table 4: List of input communication (excerpt)

| Time | Communication log                                                                 | Input to the simulation                                      |
|------|-----------------------------------------------------------------------------------|---------------------------------------------------------------|
| 1    | KLM: Approach KLM 4805 on the ground in Tenerife.                                 | inf(KLM,ATC,sameFrequency(KLM,true))                         |
| 2    | ATC: KLM- ah- 4805, roger.                                                       | ack(ATC,KLM,sameFrequency(KLM,true))                         |
| 3    | KLM: We require backtrack on 12 for takeoff Runway 30.                            | req(KLM,ATC,-taxi_clearance(KLM,unknown))                   |
| 4    | ATC: Okay, 4805... taxi... to the holding position Runway 30. Taxi into the runway and-ah-leave the runway (third) to your left. | inf(ATC,KLM,-taxi_clearance(KLM,0,2,15))                     |

4.3. Simulation result: cognitive processes

Numerous possible cognitive processes at each timestep that could explain the actual communications in the accident were output by the simulation, which is shown in Fig. 7. The number of possible cognitive processes increased at timestep 14 because PA joined the radio communication, increasing the possible number combinations of cognitive processes. At timestep 19 when visibility dropped, the number of processes increased sharply to 960, since the uncertainty involved in updating the agent’s mental states by observation increased. At timesteps like 20, 21, and 24, the set of possible communications shrunk as agents communicated to resolve uncertainty with requests or confirmations.

Figures 8, 9, 10 each show an excerpt of the possible interpretations of all communications. In the interpretation in Fig. 8, the KLM had a misconception about the taxi clearance at the beginning of the simulation, but the discrepancy was resolved through confirmation. Later at timestep 15, even though KLM could hear the communication between ATCO and PA, it did not update its bottom layer. This indicates that KLM failed to listen to the communication from ATCO to PA. As communication progresses and KLM listened to the communication from ATCO to PA at timesteps 17 and 27, the KLM successfully acquired information about PA (shown in Fig. 9). The simulation result also suggests the possibility that PA passed C3 because the pilot did not notice that his aircraft was passing C3 due to the poor visibility, which is not how the situation is described in the accident investigation report.

In the interpretation shown in Fig. 10, PA did not update its belief about its position even after it perceived that it passed the C2 taxiway (edge 8) at timestep 28. This possibility suggests that PA did not pass exit C3 intentionally but instead passed this point because it had not recognized its position previously. These results show that the simulation can account for all possibilities of each agent’s cognitive state.

Similar communication analysis is conducted manually during the analysis of actual ac-
cidents, but the analyst must infer and interpret the conditions of the relevant agents’ mental contents and how these mental contents change through communication. Each communication and action can be subject to several interpretations, however, so it is practically impossible to manually trace and analyze all possible interpretations. The proposed simulation can consider such possibilities comprehensively, thus provides a good supplement for inspectors tasked with understanding airline accidents.

![Figure 7: The number of possible processes at each timestep.](image)
| Time | Observation | Reason | Communication | Reason | KLM's process | Reason | ATCD's process | Reason | PA's process |
|------|-------------|--------|---------------|--------|---------------|--------|----------------|--------|--------------|
| 4    | REQ:        | INF    | in( ATCO, KLM, taxi_clearance( KLM, 0, 2, 3)) | INF    | KLM-ATCO:     | INF    | ATCD-KLM:      | INF    | ASS:         |
|      |             |        |               |        | taxi_clearance( KLM, 0, 2, 3, 4, 7, 10, 13, 15) |        | taxi_clearance( KLM, 0, 2, 5, 8, 9, 10, 13, 15) |        |              |
|      |             |        |               |        | => KLM-ATCO:  |        | => ATCD-KLM:   |        |              |
|      |             |        |               |        | isAvailable(3, true) |        | isAvailable(3, true) |        |              |
|      |             |        |               |        | => KLM-ATCO:  |        | => ATCD-KLM:   |        |              |
|      |             |        |               |        | isAvailable(4, true) |        | isAvailable(4, true) |        |              |
|      |             |        |               |        | => KLM-ATCO:  |        | => ATCD-KLM:   |        |              |
|      |             |        |               |        | isAvailable(10, true) |        | isAvailable(10, true) |        |              |
|      |             |        |               |        | => KLM-ATCO:  |        | => ATCD-KLM:   |        |              |
|      |             |        |               |        | isAvailable(13, true) |        | isAvailable(13, true) |        |              |
|      |             |        |               |        | => KLM-ATCO:  |        | => ATCD-KLM:   |        |              |
|      |             |        |               |        | isAvailable(15, true) |        | isAvailable(15, true) |        |              |
|      |             | INF-COMP | | INF-COMP | | | | |

| 10   | CHECK1:     | INF    | conf( ATCO, KLM, taxi_clearance( KLM, 0, 2, 3)) | CONF   | ATCO-KLM-ATCO: | CONF   | ATCO-KLM-ATCO: | CONF   | ATCO-KLM-ATCO: |
|      |             |        | taxi_clearance( KLM, 0, 2, 3) |        | taxi_clearance( KLM, 0, 2, 3) |        | taxi_clearance( KLM, 0, 2, 3) |        | taxi_clearance( KLM, 0, 2, 3) |

| 11   | CONF:       | INF    | in( ATCO, KLM, taxi_clearance( KLM, 0, 2, 3)) | INF    | KLM-ATCO:     | INF    | ATCO-KLM-ATCO: | INF    | ASS:         |
|      |             |        | taxi_clearance( KLM, 0, 2, 5, 8, 11, 14) |        | KLM-ATCO:     |        | ATCO-KLM-ATCO: |        |              |
|      |             |        | taxi_clearance( KLM, 0, 2, 5, 8, 11, 14) |        | KLM-ATCO:     |        | ATCO-KLM-ATCO: |        |              |
|      |             |        | taxi_clearance( KLM, 0, 2, 5, 8, 11, 14) |        | KLM-ATCO:     |        | ATCO-KLM-ATCO: |        |              |
|      |             |        | taxi_clearance( KLM, 0, 2, 5, 8, 11, 14) |        | KLM-ATCO:     |        | ATCO-KLM-ATCO: |        |              |
|      |             | INF-COMP | | INF-COMP | | | | |

Figure 8: An example of communication analysis(1).
| Time | Observation | Reason | Communication | Reason KLM's process | Reason ATCO's process | Reason PA's process |
|------|-------------|--------|---------------|---------------------|----------------------|---------------------|
| 15   | INF-ACK     | ack(ATC, PA)  |
|      |             | sameFrequency(PA,true)) |
|      | REQ-INF     | inf(ATC:PA,  |
|      |             | taxi_clearance(PA,0,2,5,8,9)) |
|      | LIS-ASS     | KLM-ATCO:  |
|      |             | taxi_clearance(PA,0,2,5,8,9) |
|      |             | KLM-ATCO-KLM:  |
|      |             | taxi_clearance(PA,0,2,5,8,9) |
|      | INF-ASS     | ATCO-PA:  |
|      |             | taxi_clearance(PA,0,2,5,8,9) |
|      |             | => ATCO-PA:  |
|      |             | isAvailable(5,true) |
|      |             | => ATCO-PA:  |
|      |             | isAvailable(8,true) |
|      |             | => ATCO-PA:  |
|      |             | isAvailable(9,true) |
|      | INF-ASS     | PA-ATC:  |
|      |             | taxi_clearance(PA,0,2,5,8,9) |
|      |             | => PA:  |
|      |             | isAvailable(5,true) |
|      |             | => PA:  |
|      |             | isAvailable(8,true) |
|      |             | => PA:  |
|      |             | isAvailable(9,true) |
| 27   | 3NULL       | inf(ATC:PA:reportPoint(  |
|      |             | PA,onRunway,false)) |
|      | LIS-COMP    | KLM-ATCO:  |
|      |             | reportPoint(PA,onRunway,  |
|      |             | false) |
|      |             | => KLM-ATCO:  |
|      |             | onRunway(PA,true) |
|      | LIS-COMP    | KLM:  |
|      |             | reportPoint(PA,onRunway,  |
|      |             | false) |
|      | LIS-COMP    | KLM-ATCO-KLM:  |
|      |             | reportPoint(PA,onRunway,  |
|      |             | false) |
|      |             | => KLM-ATCO-KLM:  |
|      |             | onRunway(PA,true) |

Figure 9: An example of communication analysis(2).
4.4. Simulation result: shared SA

The completeness of the shared SA as defined in Equation 1 is calculated for each possible interpretation of the overall communications. This indicator is then used to quantify the team performance. Four completeness values are calculated in the following analysis: the completeness of ATCO’s belief about KLM’s SA, ATCO’s belief about PA’s SA, KLM’s belief about ATCO’s SA, and PA’s belief about ATCO’s SA.

4.4.1. An example of Shared SA fluctuation

Figure 11 shows a time series of the SA completeness values in the interpretation of communications shown in Fig. 8. In this interpretation, the completeness of PA’s belief about ATCO’s cognition was 0 until timestep 13 and stayed relatively low (under 0.4) because PA only joined the radio communication channel at timestep 13, so that PA’s pilot could not infer any beliefs about ATCO’s cognition about KLM before timestep 13. In addition, the completeness of KLM’s belief about ATCO’s cognition decreased until timestep 27. Based on the analysis of the output table, mishearing of the communication between ATCO and PA by KLM can be regarded as the cause for this decrease and successful hearing can be regarded as the cause for the increase of completeness. As communication progressed and KLM began to listen to the communication from ATCO to PA at timestep 27, the completeness of KLM’s belief about ATCO’s SA increased. Listening to the communication between the ATCO and the other aircraft pilots helps to increase the completeness of KLA’s SA.

Incorporating this evaluation with the detailed analysis of cognitive processes in the previous subsection, an investigator can identify when and why team performance deteriorated or improved from the communications log, in addition to an overview of the communications situation. This kind of analysis is almost impossible with the typical manual analysis.
4.4.2. Shared SA in all possible scenarios

Figure 12 shows the time series of the completeness indicators as calculated from all possible cognitive processes involved in communications between the ATCO and pilots. Different-colored lines represent the results of different processes. The completeness fluctuates with a similar trend to that shown in Fig. 11 within a certain range of values. This range was caused by uncertainty in the information shared through communication and the failure to listen to other agents’ communications. The difference in the range of values among the four graphs indicates differences in the possibility for misunderstandings about the other agents. Communications with a narrow range of shared SA values are better than communications with a wide range of shared SA values.

Figure 11: Completenesses of shared SA in one set of possible cognitive processes.
5. Conclusion

This paper has presented team cognition models that apply to an ATCO and pilots, and has operationalized the cognitive processes and contents that affect team cooperation in this context. Using these models and operationalizations, we developed a simulation of team cognition for ground control operations that outputs the entire set of possible cognitive processes and contents that could explain various observable behaviors.

We demonstrated the proposed simulation and method with a case study of the analysis of team cognition involved in the Tenerife airport accident. The simulation provided various possible cognitive processes that explain the behavior leading up to the accident. Moreover, analysis of the output table and the completeness of the shared SA in each situation allows detailed analysis and easier understanding of the complicated cognitive dynamics that arise during team cooperation. The method has potential to be used for analysis of team cognition in other phases of air-traffic control like en-route control, and might be used in other fields like process control and medical operations.

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