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Analysis of work patterns as a foundation for human-automation communication in multiple remote towers

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Abstract—**Implicit communication and higher levels of automation will be more important in the future multiple remote towers, in order to make the work of the Air Traffic Controller (ATCO) more efficient. However, the ATCO still needs to be in the control loop to make critical decisions. Human-automation collaboration requires teamwork, based on common ground and implicit communication. To design automation that supports teamwork and implicit communication, the automation must know how the ATCO is working. Sensors, like eye-tracking, and work patterns of the ATCO can give important information regarding the current situation in order for the automation to provide situation based support, through implicit communication to the ATCO. This paper addresses the current lack of teamwork and implicit communication between the ATCO and the automation in today's air traffic control towers. Two case studies, using eye-tracking, were conducted. One study in a single tower simulator and one in a multiple remote tower simulator with three airports. The results show varying work patterns in three different stages of managing aircraft arrivals. This paper also discusses the potential for implicit communication and how work patterns are a foundation for designing air traffic control systems allowing teamwork.**

Keywords-component; air traffic control; implicit communication; situation awareness; common ground; multiple remote towers; automation

I. INTRODUCTION

With knowledge of the work patterns of Air Traffic Controllers (ATCO), automation can be designed to support efficient implicit communication (the things humans and systems do, individually or in teams, without verbally expressing it) between the ATCO and the automation.

In the near future, in multiple remote digital towers, one ATCO handling more than one airport at the same time (three airports in this study), is expected to be widespread. Due to the increase in workload when handling more airports, the ATCOs need more assistance, that is an access to a higher level [1, 2] of automation. The ATCO and the automation need to know their respective tasks and actions given a specific situation without having to spend valuable time on explanations and interpretations. For human-automation collaboration to be efficient the work patterns of the ATCO—how the ATCO is working and in which order he/she focuses on different parts of the screens, as well as through windows—must be investigated and visible for the automation. In order to achieve this, a sixth sense [3] like eye-tracking, could be used to provide input to the automation regarding the ATCO's work patterns. If the automation receives information about the ATCO's visual focus through sensors, like eye-tracking, the automation could adjust the information output, making the work of the ATCO more efficient.

Today, there is a low level of automation in Air Traffic Control (ATC) and a large part of the work is performed manually by the ATCO. In a tower with only one airport, where everything is done manually, it is easy for the ATCO to forget or miss crucial information [4]. The risks would be even higher in a multiple remote tower [5], where the ATCO simultaneously controls several airports. Therefore, a prerequisite for intense work in multiple remote towers is more automation that supports the ATCO with correct decisions and actions. However, along with highly automated systems and increased work efficiency, there is a risk of decreased safety if the human-automation collaboration is not adequately addressed [6, 7]. This is a major issue in many domains (e.g. aviation, health care and nuclear power plants). This paper will, however, focus on ATC and how humans and automation can work together, implicitly and explicitly, in ATC towers.

This paper presents results from two different case studies in two types of ATC towers: (1) a single tower, and (2) a multiple remote tower (with three airports), in order to investigate the differences and similarities of the ATCO's work. This is studied for three different types of events; *Continue Approach, Clear to Land* and *Taxi.* The focus of the case studies was on the variation and similarities of the ATCO's work patterns, such as their actions and use of different tools, when handling arrivals. Since implicit communication could be based on monitoring ATCO attention to visual cues and visual work patterns, an eye-tracker was used to record the eye movements of the ATCOs.

The major contributions of this paper are:

(A) comparisons of ATCOs' work patterns regarding system interaction in two different tower environments,
(B) the potential for implicit communication in ATC towers, and
(C) identification of several design challenges for implicit communication in higher levels of automation in ATC towers.

II. BACKGROUND AND RELATED WORK

A substantial volume of research has addressed automation in both aircraft and in air traffic control management and how to implement more automation to make the work of the ATCOs and pilots more efficient [7-12]. This has been done for example with speech recognition, evaluating a conflict detecting tool, autonomous conflict resolution and having autonomous ATC for airports without towers [13-17]. However, when levels of automation [18, 19] increase, strong collaboration and common ground [20, 21] between the human and the automation is required to keep the human in the control loop. Common ground develops over time and occurs when the situation changes and can be seen as a frame around Situation Awareness (SA) [22]. SA is what we know about the situation, whereas common ground is shared knowledge and assumptions. The members of the system sharing common ground can share assumptions regarding goals and communication but can have different SA.

Communication, team performance and how to avoid communication failure has been studied in many safety-critical organizations, such in aviation, nuclear power plant and healthcare [23-25]. There exists much research about communication in ATC, how the ATCOs use both implicit and explicit communication to understand and support each other, but also communication and communication failure with pilots and phraseology [25-28]. Research has shown that the lack of communication (implicit or explicit) increases the workload for ATCOs since the ATCO needs to gather and interpret information, overloading the ATCO instead of delegating [4, 29]. Communication is also necessary for teams of humans and automation as well [30-32].

With common ground and implicit communication, the SA will be easier to maintain for the ATCO since the team members (ATCO, pilot, automation) will have compatible assumptions. Implicit communication could also ease the workload since the ATCO and the automation does not have to explicitly express actions or decisions.

For the automation to understand the ATCO there needs to be an input from the ATCO to the automation. Sensors, like eye-tracking, can capture the eye movement and thereby also a vital part of work patterns in rapid work processes in environments with a high degree of visual information. The automation could potentially use these work patterns to understand how the ATCO is working (what the ATCO looks at, doing or communicating), and use that as a base to give relevant and situation based support through implicit communication.

There is research regarding common ground and distributed activities in ATC [33-35]. However, there is a lack of research regarding how common ground between humans and automation could be established in higher levels of automation in ATC. Therefore, this paper will contribute to the understanding and knowledge about implicit communication regarding common ground in ATC.

III. CASE STUDIES

Two case studies, one in a single tower (ST) simulator, and one in a multiple remote tower (MRT) simulator, were performed to study work patterns of ATCOs during three different events all handling arrivals (*Continue Approach*, *Clear to Land* and *Taxi*, see details in D).

Eye-tracking was used in the two case studies to capture the eye movements of the ATCOs and thus reveal work patterns. The use of eye-trackers in real ATC towers requires safety validations of the eye-tracking equipment. Since it was not possible to conduct such safety validations at the time of the study, the single tower case was studied in a simulator. Work in multiple remote towers is a new concept and is not in operational use, and was therefore also studied by using a simulator.

The tower simulators used in the case studies are highly advanced with a high resemblance to reality. The simulator in case study 1 (ST) is similar to the real tower being simulated, at one of the biggest airports in Sweden, and the simulator in case study 2 (MRT) is one of the first of its kind in the world, simulating three airports at the same time. Figure 1 and figure 2 illustrates sketches over the simulators used in the case studies.

In both simulators, the ATCO's workstation was equipped with an air radar and radio communication. Two pseudo-pilots (who played the roles of pilots, ground center, and ground vehicles) were needed to control the high amount of traffic and different roles (for example ground vehicles and terminal control), and in the MRT simulator, three different towers. Each simulator had an electronic flight progress strip board (strip-table). In the ST simulator, it had three columns; the left for inbound traffic, the middle for departures and the right for arrivals. In the MRT simulator it had three columns; one for each airport which were divided into several rows (arrivals, departures and so forth). In the ST simulator, the weather information was on the radar screen and in the MRT simulator, weather information for each airport was placed on the window screens. The ST simulator had ground radar as well (which simulates the only airport in Sweden which uses that), whereas the MRT simulator did not (smaller airports, under 20 arrivals/departures per day, like the ones in the MRT, do not normally have ground radar in Sweden).

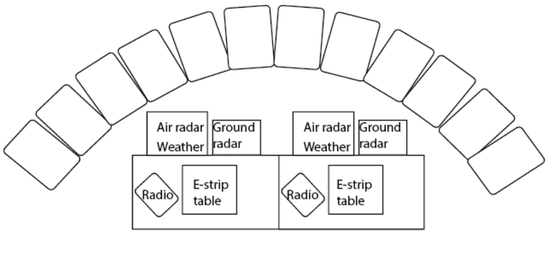


Figure 1. Sketch of the ST simulator illustrating two workstations with a total of 12 screens, air radar, ground radar, weather, radio and electronic flight strip table. Only one of the workstations were used.

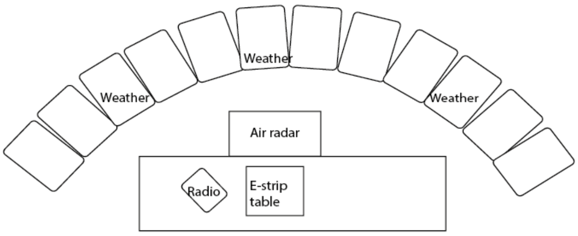


Figure 2. Sketch of the MRT simulator illustrating its 12 screens (4 screens for each of the three airports), air radar, weather, radio and electronic flight strip table

A. *Case study 1: Single Tower (ST)*

The simulated airport had three runways. Just like in real airport operations, two runways were used in the simulation, one for departures and one for arrivals (as mentioned above the studies focuses on arrivals). The ST simulator had 12 screens of 48” each to visualize the airport with runways and apron (instead of windows as in a real control tower). Both aircraft and ground vehicles could be simulated.

One licensed ATCO participated (participant 1); male, 35 years old with 7 years of experience. The ATCO had worked in simulators before and was familiar with the situation.

Four scenarios were recorded. The scenarios had different amounts of traffic (mimicking real work) and simulated daylight as well as darkness. Two of the scenarios included runway incursions and the ATCO knew that this could occur, but not how or when. In the real operative tower which was simulated, the ground service (controlling the service vehicles on and around the runway) is handled by either the ATCO or a ground service controller, depending on the amount of traffic. In the simulation, the ATCO handled either just the control zone or the control zone and the ground service.

B. *Case study 2: Multiple Remote Tower (MRT)*

The MRT simulator had three airports. The simulated airports had one runway each, like in the real airports that were simulated. The simulator had a total of 12 screens of 38” each. They visualized three airports at the same time and the 12 screens were split into four screens per airport. The ATCO could zoom into the screens making the view of one specific airport bigger when necessary. Both aircraft and ground vehicles could be simulated. The ATCO handled both control zone and ground services for all three airports, as in the real operative towers which were simulated.

Two licensed ATCOs participated in the MRT simulator case study (participant 2 and participant 3); both were male with long experience of working as tower ATCOs. Both participants had worked in the simulator before so they were familiar with the situation. Note that the participants’ familiarity (in both case studies) strengthens the validity of this study since the aim is to study regular work.

Six scenarios were recorded in this case study, three per participant. As in the ST case, the scenarios had different amounts of traffic and simulated daylight as well as darkness. In this simulation, however, no runway incursions occurred.

C. *Recordings*

The case studies took place during two days each. During the first day, the scenarios were designed (by the pseudo-pilots involved in the studies, which had been working with scenario designs before, and the main author of this paper), and the eye-tracking equipment was setup at the workstation and tested. The actual studies were conducted the following day. First, the participants and the pseudo-pilots were briefed about the study and the setup. Thereafter, the eye-tracking glasses was calibrated, a procedure that took only a few seconds, and the first scenario started and lasted for approximately 45-60 minutes. During the recording, the glasses allow the participant to move their head without the risk of losing contact with the eye-tracker. Between each scenario was a short debriefing about how the scenario had gone for the ATCOs and the pseudo-pilots and if they felt comfortable.

The eye-tracking glasses used in case study 1 were Tobii Glasses 2 and the glasses used in case study 2 was Tobii Glasses 1 [36]. Both glasses record what the participants are looking at in real time, (30 Hz frequency for Glasses 1 and 60 Hz for Glasses 2). To capture eye movements, glasses 1 uses IR-markers placed on the air traffic management tools and screens. For Glasses 2 this kind of markers is not necessary since these glasses have the IR lights built into them and record everything the participant looks at and not only the specific areas (where the markers are placed), as Glasses 1. The different setup of infrared (IR) lights means that the two types of glasses require different analysis software to analyze data. For the Tobii Glasses 1 the analysis software Tobii Studio was used and for Tobii Glasses 2 the Tobii Glasses Analysis Software was used. It is important to mention that even though there were two types of eye-tracking glasses they are alike in the design and usage for the participant and the data collected with them are easy and reliable to compare.

The pilots’ communication in case study 1 was played through a speaker placed beside the ATCO and the eye-tracking glasses recorded their communication, through a microphone on the glasses. In case study 2 the communication from the ATCO was recorded through the glasses. The pilots’ communication was recorded separately and could not be heard in the analysis software used to identify eye-patterns. Because of this, the pilots’ communication could not be used in the second case study. However, the focus of the study was not on the communication from the pilot, rather on the work of the ATCO and what he was looking at.

In both case studies, a camera was placed at the back of the simulator room to record the ATCO and the simulator and several pictures were taken of the entire scene, the screens and the workstations. This aim was to capture events that were not recorded by the eye-tracker, such as the screens when the ATCO did not look at them, and to recall details during the analysis process.

D. Analysis of data: Episode Analysis

To be able to analyze the work of the ATCOs in the different tower environments, eye-tracking with an in-depth episode analysis was used. Episode analysis consists of dividing big audio or video datasets, such as the scenarios from the two case studies, into shorter episodes for in-depth transcription. Eye-tracking studies in ATC has been made before [37] but using only quantitative methods for eye-tracking studies would provide big gaze samples with unreadable gaze plots [38]. However, to understand how the ATCO is interacting with the system transcriptions of the recordings were made. Lundberg [39] created a holistic framework for SA and used examples from ATC towers with episode analysis. Another study by Rankin, Dahlbäck and Lundberg [40] used episode analysis as a method regarding communication in the Swedish Response Team. The method was used to understand the processes taking place during improvised work ''as it happens'' in the response team. By using episodes and sub-episodes they could provide a map of how information was transmitted through the organization. Other work, [29, 41], has also used an eye-tracker and episode analysis to map how ATCOs used different air traffic management tools. Episode analysis turned out to be successful in mapping the ATCOs' eye-movements and to understand how the ATCOs used the different tools. Therefore, episode analysis was considered as the most suitable analysis for this study since it provides information and an understanding for how the ATCOs are working with the different tools and screens.

Episodes (sections of 15-30 minutes from the recorded scenarios) containing arrivals were the focus for the analysis of data from both case studies, because arrivals are events (among others) which require high SA and the need for the ATCO to look at the runway, the radar and the strip-table (e.g information distributed in several areas of the workstation). During the analysis, an arrival was classified into three different events; *Continue Approach*, *Clear to Land* and *Taxi*. The event *Continue Approach* is when an aircraft is contacting the tower for clearance to continue approach towards the final. The event *Clear to Land* is when the aircraft gets clearance for landing on the runway and the event *Taxi* is when the aircraft gets information to contact the taxi service to the airport to leave the runway.

In total 12 episodes, including the three different types of events described above, from both the simulators were identified and analyzed. Table 1 shows for which type of tower, which participant, type of traffic in that episode and if the episode were during daylight or darkness. In "Type of traffic" AFCT stands for aircraft, IFR for instrument flight rules (the aircraft is flown by the pilot without outer references, only with instruments in the aircraft) and VFR stands for visual flight rules (the aircraft is flown by references from outside visual clues). The type of traffic is documented to get an understanding of how much the ATCO had to do during the entire scenario.

Since the episodes were in the time range of 15-30 minutes and with focus only on arrivals, the number of vehicles in the specific episode are not relevant. For the ST, there were no specifics for exactly how much traffic there would be in every scenario, only that there would be so much traffic as a regular day at that airport. Therefore, in table 1 for type of traffic in the ST, it states "normal traffic". In episode 3 and 4, the ATCO had normal traffic but the pilots in the simulator had planned for runway incursions as well, which the ATCO knew of. In the MRT simulator, the traffic was higher than during a regular day at the three airports. Since the three airports simulated are so small, however, only a few arrivals happen per day.

The 12 episodes of interest with arrivals, extracted from the eye-tracking videos, were watched from the beginning to the end in the analysis software with the eye-gaze data activated to be able to follow the participants' eye movements. Eye-movements provide information of where the ATCO has looked on the different screen and tools, when and in which order. Such information gives knowledge about work strategies and work patterns, which can be used to design new ATC systems or automation that take into account information from such sensors.

The episodes for the ST were defined as the point when the pilot contacted the ATCO for the first time (access to communication from the ATCO and the pilot) for an arrival until the last time the ATCO had contact with that specific aircraft. For the MRT the episodes were defined from that the ATCO spoke to the aircraft for the first time for an arrival (no data for the communication from the pilots) until the last time the ATCO had contact with that specific aircraft. What the ATCO was looking at right before the contact with the pilot and right after the contact with the pilot was also documented.

As mentioned before, the episodes from the two towers were broken into three main events; *Continue Approach*, *Clear to Land* and *Taxi* (which lasted only a couple of

TABLE 1. EPISODES FROM THE EYE-TRACKING VIDEOS WITH TYPE OF TOWERS, PARTICIPANT, TYPE OF TRAFFIC FOR EACH SCENARIO, THE NUMBER OF GROUND VEHICLES FOR EACH SCENARIO AND IF THERE WAS DAYLIGHT OR DARKNESS

Episode number	Type of tower	Ground radar	Participant	Type of traffic	Daylight / Darkness
ST-normal 1	Single tower	Yes	1	Normal traffic	Daylight
ST-normal 2	Single tower	Yes	1	Normal traffic	Daylight
ST-incursion 3	Single tower	Yes	1	Runway incursions	Daylight
ST-incursion 4	Single tower	Yes	1	Runway incursions	Daylight
MRT 5	Multiple tower	No	2	30 AFCT IFR/VFR	Daylight
MRT 6	Multiple tower	No	2	30 AFCT IFR/VFR	Daylight
MRT 7	Multiple tower	No	3	30 AFCT IFR/VFR	Daylight
MRT 8	Multiple tower	No	3	30 AFCT IFR/VFR	Daylight
MRT 9	Multiple tower	No	2	12-14 AFCT IFR/VFR	Daylight
MRT 10	Multiple tower	No	3	12-14 AFCT IFR/VFR	Daylight
MRT 11	Multiple tower	No	3	12-14 AFCT IFR/VFR	Darkness
MRT 12	Multiple tower	No	2	12-14 AFCT IFR/VFR	Darkness

seconds each). During the main events, activities performed by the ATCO were captured and analyzed (ATCO looking at or interacting with air radar, e-strip, ground radar, radio, communication with the pilot, weather, runway) through in-depth transcriptions. The different activities performed by the ATCO were color coded in the transcription (table 2).

When every episode had been transcribed (time, what the ATCO was looking at and saying and if anything else happened), a comparison was made between the different episodes and the different tower environments to investigate and establish if there were any patterns in the ATCOs' way of working with arrivals. The comparison consisted of what the ATCOs were looking at (and in which order) and what they were saying.

Table 2 contains the activities the ATCOs perform during the three events in the two different towers. Each activity is color coded and is illustrated in tables 3-5 for the three analyzed events for all of the episodes. Communication between ATCO and pilot is not in tables 3-5 since the communication is ongoing over other activities.

IV. RESULTS

The analysis shows that ATCOs in both of the towers had communication with the aircraft at least one time for every of the three events (table 4), and for every episode (except episode 5, 6, 8 and 12 which did not have the event *Continue Approach*). Radio usage is an activity performed several times by the ATCO in almost all of the episodes for all events in both towers. Another activity found in every event was work with the air radar. For the ST, the ATCO looked at the air radar during every event, but not in every episode. For the event *Continue Approach*, the ATCO started all of the episodes by looking at the air radar, to locate the aircraft. In the event *Clear to Land* the ATCO looks again on the air radar but the patterns are not as clear here. During *Taxi*, in contrast, the ATCO ends the event by looking at the air radar, probably to find the next aircraft on the radar to interact with.

In the ST simulator, in the event *Continue Approach*, the first thing the ATCO does when a pilot is contacting the tower for the first time is to look at the air radar. The ATCO has probably already seen the aircraft on the air radar when he scans the environment for incoming traffic, but when the pilot contacts the tower the ATCO check the air radar to see exactly where the aircraft is (table 5). The second thing the ATCO does is to look at the aircraft's e-strip, this to make sure the information the ATCO received is correct (table 5).

The event *Continue Approach* is not even performed in the MRT for episodes MRT 5, MRT 6, MRT 8 and MRT 12, rather the ATCO clears the aircraft to land at first contact. However, the ATCO looks at the different tools in a certain order when handling arrivals. There are clear patterns in the MRT that for all the events the ATCO looks at the radio before contacting the aircraft, then looks at the e- strip, the runway or weather information (depending on the event) and then the e-strip again. There is a clear pattern that the ATCO in the MRT always looks at the e-strip for the specific aircraft at least once for every event.

The ATCO looks at the e-strip for the specific aircraft on the strip-table in every episode in the ST before answering the pilot for the first time. The ATCO manually moves the e-strip to the right section of the arrival column on the strip-table for every event.

For every event in the ST (except ST-normal 2, event *Taxi*), the ATCO looks at the ground radar before or while he clears the aircraft to land (table 3 and 5). In ST-normal 2, event *Taxi*, the ATCO do not look at the ground radar at all (table 5).

In the event *Clear to Land*, the ATCO in both towers always concludes the episode by looking or interacting with the strip-table (except for ST-incursion 3 and MRT 9).

In the event *Taxi*, ATCOs in both towers looks at the runway at least one time in all episodes (except MRT 7) and the first activity the ATCO do in the ST is to look at the runway before contacting the aircraft (table 5).

V. DISCUSSION

Visual cues for deviations and visual information are the most important source of information for the ATCO, to maintain situation awareness in current ATM systems. Thus, sensors, like eye-tracking, could provide the automation with information about work patterns based on the sensor input (e.g. visual scan patterns). Potentially, this could be used to give situation based support through implicit communication. Today, there are sensors outside the system, e.g. radar views, to collect information about the situation per se. However, there are no sensors within the system to collect information about what the ATCO is doing, e.g. like the eye-tracking system used in this study, to see where the ATCO is looking. The automation does not know in today's system what the ATCO is doing or what is being communicated, and therefore is a lack of implicit communication.

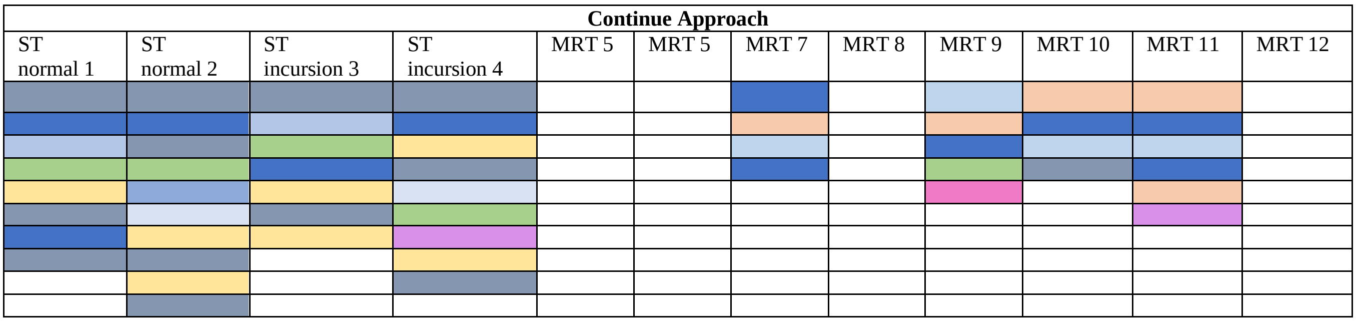
Implicit communication and teamwork will be even more important in multiple remote towers, where each ATCO controls several airports, with the potential to make the work of the ATCO safer and more efficient. However, a first step toward this goal is to study work patterns – in this case mainly visual patterns – to uncover to what extent the patterns can be indicative of what the ATCO is doing (e.g. clearing an aircraft for landing). This is needed to discover e.g. potential omissions, what the ATCO has not attended, in the scan patterns.

This article has described the work and patterns of an ATCO in two different tower environments, a single tower and a multiple remote tower. Since the ATCO works primarily with visual clues, the focus was on what the ATCO was doing and looking at (the verbal communication between ATCO and pilots was a secondary concern).

TABLE 2. OVERVIEW OF COLOR CODED ACTIVITIES IN ST AND MRT FOR THE THREE EVENTS *CONTINUE APPROACH*, *CLEAR TO LAND* AND *TAXI*

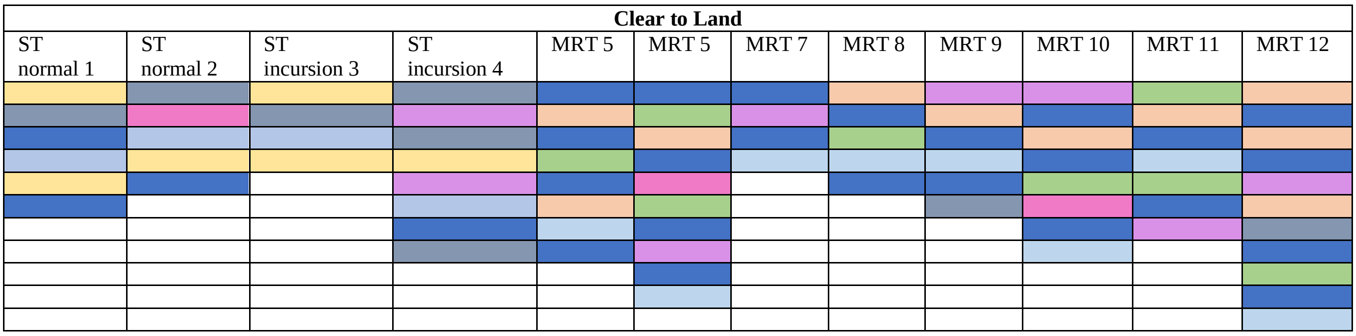
	Single tower (ST)			Multiple remote tower (MRT)		
	Continue Approach	**Clear to Land**	**Taxi**	**Continue Approach**	**Clear to land**	**Taxi**
Air radar	■	■	■	■	■	
E-strip	■	■	■	■	■	■
Ground radar	■	■	■			
Radio				■	■	■
Communication	■	■	■	■	■	■
Weather	■				■	
Runway			■			■
Interact with strip-table	■	■	■	■	■	■
Above runway	■	■	■	■	■	■

TABLE 3. ACTIVITIES FOR THE EVENT CONTINUE APPROACH FOR ALL EPISODES (1-12). EACH COLOR REPRESENTS AN ACTIVITY. (COMMUNICATION IS AN ONGOING PARALLEL PROCESS WITH THE OTHER ACTIVITIES, THEREFORE NOT LISTED)



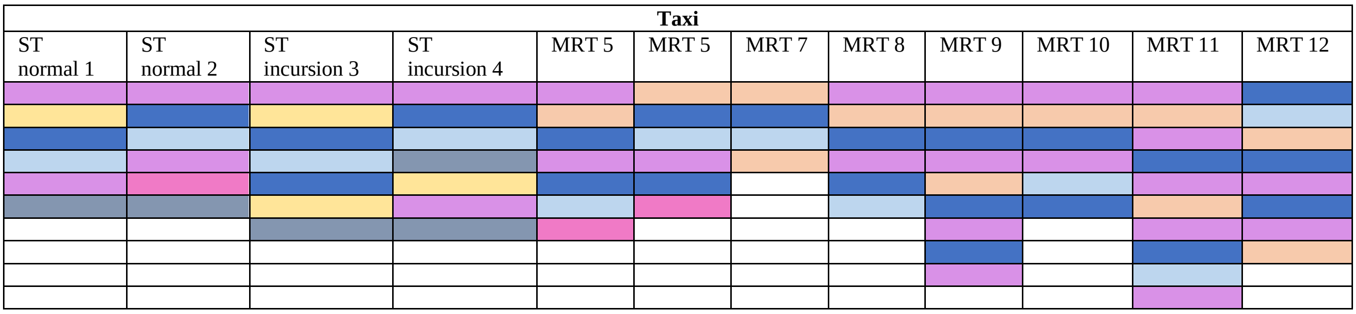
Continue Approach											
ST normal 1	ST normal 2	ST incursion 3	ST incursion 4	MRT 5	MRT 5	MRT 7	MRT 8	MRT 9	MRT 10	MRT 11	MRT 12

TABLE 4. ACTIVITIES FOR THE EVENT *CLEAR TO LAND* FOR ALL EPISODES (1-12). EACH COLOR REPRESENTS AN ACTIVITY. (COMMUNICATION IS AN ONGOING PARALLEL PROCESS WITH THE OTHER ACTIVITIES, THEREFORE NOT LISTED)



Clear to Land											
ST normal 1	ST normal 2	ST incursion 3	ST incursion 4	MRT 5	MRT 5	MRT 7	MRT 8	MRT 9	MRT 10	MRT 11	MRT 12

TABLE 5. ACTIVITIES FOR THE EVENT *TAXI* FOR ALL EPISODES (1-12). EACH COLOR REPRESENTS AN ACTIVITY. (COMMUNICATION IS AN ONGOING PARALLEL PROCESS WITH THE OTHER ACTIVITIES, THEREFORE NOT LISTED)



Taxi											
ST normal 1	ST normal 2	ST incursion 3	ST incursion 4	MRT 5	MRT 5	MRT 7	MRT 8	MRT 9	MRT 10	MRT 11	MRT 12

The contributions of this study are:

A) comparisons of ATCOs' work patterns regarding system interaction in two different tower environments,

B) the potential for implicit communication in ATC towers,

C) identification of several design challenges for implicit communication in higher levels of automation in ATC towers.

The contributions will be described and discussed for in this section.

A. *Work patterns to support implicit communication*

Work patterns must be clear and regular for the automation to use it, to infer what kind of activity (e.g. landing clearance) they represent. The three events, *Continue Approach*, *Clear to Land* and *Taxi*, occur in both towers. However, as the results from the two case studies show, the work patterns differ between the two towers.

For instance, in most of the episodes in the MRT simulator, the ATCO gave information about the wind to the pilot in the event *Clear to Land* (table 4). The ATCO in the ST simulator chooses to give weather information during the event *Continue Approach* instead (table 3). The ATCO can choose when to give information, and it depends on how close the aircraft is. This illustrates that different ATCOs work in different ways and have their own procedures and may not be a product of the type of tower they work in. Both the tower environment and the ATCO can affect work patterns. For example, the MRT simulator does not have ground radar and therefore the work patterns will differ from the ST, indicating the tower environment affected the work patterns. When the ATCO gave information about the wind in different events, the work patterns was a direct cause of different ATCOs. This means, the automation must adapt to such differences and especially adapt to the ATCO, since it is the ATCOs' work patterns that are the foundation for implicit communication (to enable situation based support).

B. *Implicit communication through sensors in ATC*

In today's ATC towers, there are some activities that must be conducted to clear an aircraft to land. In table 4 for the ST, the ATCO is always looking at the ground radar to make sure no vehicles are on the runway. In the same table for the MRT simulator, the ATCO is always looking at the strip-table to check the call sign and information about the aircraft. The results show that the ATCO does not get support from today's system, instead the ATCO has to manually find this information on his own. With more support, the ATCO could receive information about the runway and the time to arrival at the same time, so the ATCO do not have to manually calculate the arrival time and cross match it with the activities on the runway.

As shown in the episodes, the eye-tracking data itself is insufficient for finding patterns in current operational concepts and system designs, due to the variations in interactions. For the system and ATCO to achieve common ground through enhancing the automation with support for implicit communication, it might therefore also be required to have other sensors, not only eye-tracking to know where the ATCO are looking. It could, for instance, be of use to include data regarding what the ATCO writes on the strip-table and what is communicated between the ATCO and the pilot (the communication between ATCO and pilot was not the focus of this study). Other sensors, like heart rate or pulse, can also be used to map the work of the ATCO to design implicit communication for human-automation collaboration in ATC systems.

C. *Design challenges for implicit communication in ATC*

One of the purposes of this paper was to identify design challenges of implicit communication in air traffic control towers. It has been seen that the concept of operations in ATC is dependent on the design of the environment. The design of the environment would affect both implicit and explicit communication between the members of a team. If the ATCO knows where to find information (resulting in clear patterns without visual search), he automation could infer what the ATCO is doing based on that. The dependency between patterns and the design of the operating procedures and environment is, however, an issue. The design of the environment will affect the work patterns, which could affect the support from the automation. For example, the design of the radio in the MRT simulator makes the ATCO look at the radio in 19 of 24 episodes (table 3-5). In the MRT simulator, the ATCO had to turn his head and press the right button on the radio to reach the right frequency depending on which airport it required. If the design of the radio would be different or if the automation knew which airport the ATCO was looking at, the frequency would change for him. This information could thus be served by the automation instead, based on implicit communication about the current ATCO task, to avoid that the ATCO need to find information on his own. However, if communication between the automation and the ATCO changes, the work patterns will change as well. Implicit communication will also change the work patterns and this is something the automation needs to adapt to. The situation will affect the ATCO. It is a circle of consequences and impacts, which is the design challenge. The environment must be designed to create clear work patterns the automation could use, through input and sensors, to give situation based support. The design will affect the work patterns and thereby affect the support and the implicit communication. This is a potential trade-off (clear patterns versus efficient patterns). A baseline for comparison of implicit communication with other alternatives, in future studies, could, for instance, be operations without implicit communication, or explicit communication (manual entry) about ATCO tasks.

D. *Today's and tomorrow's multiple remote towers*

Even though the MRT simulator is more advanced than in single (digital or traditional) towers, in current designs there is still a lack of implicit communication between the ATCO and the system. The system does not have more information about what the ATCO does, than in an ST, even though there are more airports. With more airports, it is important the ATCO and the system can communicate implicitly to avoid misunderstandings and to lower the workload for the ATCO. Since there is no ground radar at small airports (an important market for multiple remote towers), the ATCO looks at and depends more on the visual clues (not the implicit information provided by the system) from the runway through the window (or camera view). Currently, the ATCO is left alone to interpret that information, instead of getting support by the automation. With a ground radar, the ATCO have two sources of information (the ground radar and the visual clues from the runway and apron). With automation that supports implicit communication, the ATCO could receive information from different areas based on the work patterns.

Involving a higher degree of automation in monitoring, decision making and as cognitive support for the ATCO, could thus potentially lead to even more efficient work. An increased amount of traffic could be easier to handle. There are, however, some challenges that must be addressed. When using automation as a reminder and a helper for where to look and what to do there is a chance for false alarms. The automation (with input from an eye-tracker) might not have picked up on the signal that the ATCO has looked at the runway and therefore indicate to the ATCO to do so. This can lead to the need for double-checking for the ATCO and misplaced attention and SA, which in turn can lead to false common ground. Common ground between the operator and automation is thus something to investigate further. Teamwork, how the information is cross-checked and what happens when there is a lack in common ground and a lack of mutual knowledge and assumptions are key factors. Further studies on multiple remote towers, with different designs, must, therefore, be done to see how the ATCO can work with several airports at the same time and how common ground can then best be established through implicit communication when the attention is distributed over several areas.

This study suggests that eye-trackers can be used as sensors in future ATC systems, for implicit communication. Eye tracking was also used as a data collection tool in this study. The case studies presented in this paper used eye-trackers and a qualitative approach to the data set. Our analysis shows that eye-tracking is needed to infer how the ATCOs are working in such complex visual environments as ATC. A different approach to qualitative analysis would be to perform a quantitative analysis. This would also be needed for future systems that rely on implicit communication. Compared to the qualitative approach this method would provide information including, for example, time and errors for different tasks and environments. Research within data mining could also enable big data sets, a significantly larger number of users and tasks. However, a quantitative approach will not capture the meaning and understanding of the ATCOs choices. At present, this requires human interpretation (e.g. through episode analysis), which may be reduced through, for example, sequence mining [42, 43]. Quantitative studies on this topic either require a substantial set of experiments, or eye-trackers that are validated for safety and installed in real towers.

VI. CONCLUSIONS

The potential to have more airports than three, as in this study, or more complex or intense traffic, depends on the quality of human-automation collaboration.

To sum up the challenge and opportunity for ATM, there is a lack of implicit communication in today’s air traffic control towers. Therefore, with more airports, as in a multiple remote tower, there is a requirement for more and higher levels of automation which supports the ATCO and can implicitly communicate with the ATCO. Today, the ATCO has to interpret and manually find information, but if the automation could use the work patterns of the ATCO the automation could be able to give situation based support. The first step towards that is the use of sensors, like eye-tracking, which could provide the automation with knowledge about the ATCO’s work patterns.

The main challenges discussed in this paper are:

- The variation in work patterns between different ATCOs.
- The interdependence between work patterns, the design of the environment, and the use of implicit communication to aid the ATCO (affecting work patterns).
- The issue of imperfect sensors, giving the automation an erroneous view of ATCO work, in short issues of establishing common ground that also occurs between humans.

The challenges are opportunities for a future with situation based support implicit communication between the ATCO and the ATM system, through work patterns.

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