Understanding Human-Human Collaboration to Guide Human-Computer Interaction Design in Air Traffic Control

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Abstract – *With increasing sophistication of automation in recent years, interaction between humans and automated systems has shifted from humans using automated tools to humans and automated systems "collaborating" with each other. In designing human-computer interactions in complex systems, researchers have drawn analogies between human-computer interaction and human-human collaboration. Although "collaboration" seemingly implies achieving shared goals between equitable partners, collaboration often involves partners who have different levels of authority and responsibility. One such environment is air traffic control (ATC) operations, in which controllers manage air traffic safely and efficiently with cooperation from pilots. This paper examines the nature of collaboration between controllers and pilots in current and future ATC operations. Key factors that drive human-human collaboration style in ATC are discussed. These factors are applicable to the design of automation and decision support tools in future ATC operations.*

Keywords: Collaboration, automation, air traffic control, interaction design, human-computer interaction

1 Introduction

Automation is becoming more ubiquitous as computer systems become increasingly powerful and adaptive to their environment. One approach to automation design has been to eliminate human variability out of complex systems by taking human operators out of the control loop and replacing them with automation. Such design has been proposed in various complex systems, such as next generation air traffic control system [1] and computer network system administration [2].

Despite recent advances, however, fully automated systems that can make complex decisions without human supervision are not yet viable, making ongoing research in human-computer interaction still relevant. Increasing decision-making capacity of automation and decision support tools has spurred research into human-computer collaboration in which computer form a partnership with the operators [3]. Terveen [4] describes five fundamental aspects of collaboration in following manner:

- Agreement on the shared goal(s) to be achieved
- Planning, allocation of responsibility, and coordination of actions between participants to achieve the shared goal(s)
- Ability to track progress toward their goals and establish a shared context
- Concrete definition of the goals and negotiation process to achieved the goals
- Adaptation between participants to each other and the situational context

By drawing analogies between the ways humans collaborate, sophisticated automated systems can be designed to "collaborate" with its operators. However, an implicit assumption in making analogies between human-computer interaction and human-human collaboration is that the latter is well understood. Research in this field has focused on describing and understanding general human-human collaboration styles. However, in reality, different operational domains have unique situational constraints that result in different collaboration styles. For example, in air traffic control (ATC) systems, distinct collaborative styles among the human operators (e.g. controllers, pilots, traffic management advisor, etc.) have emerged due to stringent time and safety constraints of ATC operations. This paper describes the nature of those constraints and resulting collaboration styles among pilots and controllers in both current and future ATC operations. If human-computer interaction design in ATC domain is to be guided by analogies to human-human collaboration, domain-specific factors that drive the human-human collaboration styles in ATC domain should first be understood.

In the following sections, distribution of tasks, responsibilities, and control among different controllers and pilots in present-day operations are briefly described. Observations of ATC operations have led to three interdependent factors – i.e. locus of responsibility vs. control; balancing time, workload, and safety constraints; and maintaining shared situation awareness – as key factors that drive human-human interactions in the ATC domain. Accordingly, these factors have played a critical role in future ATC concepts that were tested in the human-in-the-loop (HITL) simulations at NASA Ames Research Center [5,6,7], in which tasks and responsibilities were redistributed among controllers, pilots, and air/ground automation.

Given that these three factors play a critical role in emergent human-human collaboration styles, they are also likely to have a significant impact on human-computer interactions, suggesting that future controller/pilot decision support tool designs should be guided by the same set of factors. Potential guidelines for appropriate tool designs that meet the ATC domain-specific constraints are discussed in the last section of the paper.

2 Air Traffic Control Operations

For anyone who is unfamiliar with ATC operations, an air traffic controller's job entails keeping a safe separation distance between aircraft and managing air traffic flows by "directing" the planes where to go. S/he can issue a directive, called a *clearance*, such as "United 301, turn left heading 030, vector for traffic." to instruct a pilot to turn his/her plane left on a heading of 30 degrees on an extrinsic (absolute) reference frame. The controller may add the reason for the clearance, as was done in this situation in which the heading change was due to another plane in its path.

En route and terminal approach controllers monitor planes as they fly between airports, keeping track of them via radars. Controllers monitor the traffic patterns and make certain that planes stay a safe distance apart, which is generally 5 or 3 nm lateral and 1000 ft vertical separation. Violations of these separation requirements are treated seriously, as controllers may lose their jobs permanently regardless of the situational context that led to the violations. They manage the traffic by instructing pilots when they need to change their altitude or heading in order to avoid other planes or bad weather. Tower controllers manage the flow of aircraft that are landing and taking off. They also determine the best way to bring in and send out flights to reduce delays. Tower controllers look out tower windows and use radar to track planes.

Depending on the traffic density, there are one, two, or three air traffic controllers for a given partition of airspace called a "sector". The *radar associate controller* receives the flight-plan information anywhere from five to 30 minutes prior to an aircraft entering that sector. The associate controller works with the radar controller who is in charge of that sector. The *radar controller* is in charge of all air-to-ground communication, maintains safe separation of aircraft within the sector and coordinates activities with other sectors and/or centers. Another controller, called the *radar hand-off controller*, assists the radar and associate radar controllers during times of heavy traffic, watching the radar screen and helping to maintain smooth air-traffic flow. Together, they monitor the aircraft until it leaves their sector into an adjacent sector [8].

On the flight deck of a commercial aircraft, two pilots usually make up the cockpit crew. Generally, the most experienced pilot, the *captain*, is in command and supervises all other crew members. The captain and the co-pilot (called the *first officer*), share flying and other duties, such as communicating with air traffic controllers and monitoring the instruments. Some large aircraft have a third pilot, but virtually all new aircraft now fly with only two pilots, who rely more heavily on automation. With the assistance of autopilot and the flight management system (FMS), pilots steer the plane along their planned route and are monitored by the air traffic controllers throughout the flight. Pilots may request a change in altitude or route if circumstances dictate. The request may be made to find a smoother ride, a stronger tailwind, or a weaker headwind to save fuel and increase speed.

3 Key Factors that Drive the Collaborative Behavior in ATC

3.1 Responsibilities and Control

In air traffic control systems, safety is the utmost important factor. In addition to checks and redundancies that are in place in the operational procedures to ensure safety, safety is ultimately maintained by holding controllers responsible for the separation requirement and by holding pilots responsible for the safety of the aircraft. Since controllers and pilots are ultimately responsible for the safety, the locus of control generally resides with the human operators who bear the safety responsibility. To have a proper awareness of the situation, a controller and/or a pilot needs to initiate or be informed of actions taken by other operators and/or automated systems. The intent of these actions needs to be transparent to the responsible operator, meaning that the actions need to be predictable and easily monitored by him/her.

3.2 Time, Workload, and Safety Constraints

Two factors that have opposite effects on communicative behaviors are safety and time pressure. During a busy traffic problem, controller workload and voice congestion over the radio frequency are high. The clearances need to be executed in a timely manner to ensure safety since there may be potential conflicts with other aircraft in the near future. In a time-critical environment, communications between controllers and pilots need to be minimal so that controller workload and frequency congestion are as low as possible. To reduce ambiguity and minimize the length of phraseology, clearances are constructed so that each utterance in the clearance serves a specific function and the listening party has a clear expectation as to what s/he will hear. With the separation responsibility in the hands of the radar controllers, pilots generally defer to controllers in their verbal exchanges without much questioning and/or negotiations. Despite the need for minimal communication, safety requires checking the clearances for errors. Pilots read back the clearances issued by the controllers to jointly check on the clearances to be executed. Readbacks are cruicial since a simple misunderstanding of the callsign or the altitude can lead to an accident. Sometimes, standard phraseology can be quite long because a shorter phraseology may introduce potential ambiguity and misunderstanding.

3.3 Shared Situational Awareness

Communications between the controllers are also kept to a minimum. They leverage shared goals, situational awareness, and well-defined task delegation to communicate quickly without much verbal communication. With the radar controller in charge, radar associate and radar hand-off controllers have delegated tasks that they perform in parallel to reduce the radar controller workload. They also act as extra sets of eyes to monitor potential conflicts. Communications between controllers can be very subtle. For example, a radar associate who detects a potential conflict between two aircraft may alert the radar controller by simply pointing at the aircraft. Pointing is sufficient for the radar controller to infer the intent of the radar associate because under the situation, it is the most logical meaning behind the gesture. This example illustrates how controllers use shared knowledge and goals to communicate with minimal words and gestures. Controllers and their support tools work seamlessly together as a single entity that maintains safe operations in present-day operations [9]. Similarly, the flight crew in a cockpit also coordinates actions through subtle communication cues that rely heavily on the shared knowledge and goals [10].

4 Human-Human Collaboration in Future Air Traffic Management

Air traffic control operations offer a unique style of human-human collaboration that has emerged from controllers' and pilots' safety responsibilities, as well as time, workload, and safety constraints in ATC operations. To manage in such an environment, explicit verbal communications are minimized by relying on well-defined procedures/phraseology as well as significant leveraging of shared goals, intent, and situational knowledge. These factors played a significant role in the development of future air traffic control concepts tested at NASA Ames Research Center [5,6,7]. A brief description of the concepts and the relevant collaboration results are described in the following sections.

4.1 Terminal Arrival Self-Spacing

Aircraft equipped with flight deck spacing tools use them in the terminal area to maintain proper spacing with a lead aircraft in an arrival stream. Terminal Radar Control (TRACON) controllers issue clearances to equipped aircraft to designate the lead aircraft and self-spacing time interval to be maintained. This concept delegates the spacing task to pilots and flight deck automation to deliver aircraft more efficiently to the runway while potentially lowering the overall controller workload. The separation responsibility remains with the controller. The results from a HITL study showed that while self-spacing aircraft produced more efficient spacing between aircraft, they were considered less safe by the controllers [5]. Delegation of the spacing task to the pilots and flight deck automation, while leaving the separation responsibility to the controllers, was unacceptable to the controllers. The controller participants commented that the concept would have been more acceptable if the separation responsibility was also given to the pilots along with the spacing task responsibility. This finding suggests that the responsibility and the control of an action should not be distributed among different human operators.

4.2 En Route Trajectory Negotiation

In en route trajectory negotiation concept, pilots use their decision support tools (DSTs) to develop conflict-free flight path changes, which are sent as trajectory change requests (pilot to controller) or trajectory clearances (controller to pilot) using controller-pilot data link (CPDLC). While flight path changes can be proposed by either party, the responsibility for maintaining separation lies exclusively with the controller. In the HITL study that examined this concept [6], the negotiation process was minimal. Pilots sent a preferred trajectory via CPDLC and controllers responded by either accepting or rejecting the request. With the rejections, controllers gave their reasons by voice why the request was rejected. A more extensive negotiation process was ruled out because it was assumed that time and workload constraints on the controllers did not allow them to engage in a lengthy negotiation process. Feedback from the controllers and pilots after the study supported this assumption. The pilots were comfortable with simple acceptance/rejection of their requests and the controllers thought that it should not be longer given that they need to perform other more pressing tasks. They also commented that for a given traffic situation, controllers could easily infer the reason for a particular request – e.g. avoiding bad weather, direct routes to the next waypoint, etc. This shared knowledge of the situation allows the communication between controllers and pilots to be minimal and still be adequate.

4.3 En Route Free Maneuvering

The en route free maneuvering concept explores the potential benefits of delegating responsibility for maintaining separation to the flight crews of properly equipped aircraft. Free maneuvering aircraft may modify its flight path without controller's approval, as long as new conflicts are not created. Controllers are not responsible for the separation between free maneuvering aircraft. The results from a HITL simulation study [7] suggested that unambiguous delegation of both the responsibility and the separation task to the pilots and flight deck automation led to a successful management of increased traffic levels without a significant increase in controller workload. However, when conflicts remained unresolved within minutes of separation errors, ambiguities in the roles and responsibilities arose due to additional safety procedures in the simulation. When a pilot-controlled free maneuvering aircraft did not resolve an impending conflict with a controller-managed aircraft, the conflict was alerted to the controller at 3 minutes to the loss of separation (LOS). The controller had an option of contacting the pilot to ask for his/her intent or to intervene and move the controller-managed aircraft to maintain safety. The results from the study revealed that the controllers did not have enough time to gain sufficient situation awareness of the conflict, alert the pilots, and intervene appropriately within the 3 minute time span. A longer lead time to assess the conflicts may have allowed the controllers to gain adequate situation awareness of the impending conflict and appropriately coordinate a plan of action with the pilots.

5 Human-Automation Collaboration in Future Air Traffic Management

Future ATC operations that were described in the previous sections were only possible with advanced automation and decision support tools at both the controller stations and the cockpit. Not only were the tasks and responsibilities re-distributed between controllers and pilots, but many of the tasks were delegated to automation. Interactions between controller and flight deck DSTs and their human counterparts would require a similar examination of the collaboration principles as those examined in the human-human collaborations. In short, human-computer collaboration styles should adhere to the constraints established by the three key factors – i.e. responsibility/control, time/workload/safety constraints, and shared situation awareness – that impacted the human-human collaborations.

5.1 A Framework for Automation Design

Computers are increasingly capable of automating functions that used to be performed by human operators. As humans and computers work together to perform system functions, however, it has become clear that automation changes human operator's activity such that new coordination demands are put on the human operator. The coordination between human and computers can be challenging due to different "expertise" that each brings. For example, in ATC operations, controllers show superiority to the automation in recognizing complex situations while computers show potential for improving traffic efficiency and throughput using sophisticated algorithms. Collaborative human-computer systems in air traffic control should specify a division of labor between human operators and computer systems according to their asymmetric abilities while designing a communication mechanism that can coordinate their actions and intents in a manner that is understandable to each other.

Parasuraman, Sheridan, and Wickens [11] proposed a general framework for automation design in human-computer systems. They categorized system functions into four stages – i.e. *information acquisition, information analysis, decision/action selection,* and *action implementation* – that roughly correspond to various stages of human information processing. They proposed that different levels of automation, from fully manual to fully automated, should be selected separately for each of the stages based on *primary* and *secondary evaluative criteria*. *Primary evaluative criteria* are based on human operator performance in the system after automation has been implemented and the resulting consequences of the changed performances in areas such as mental workload, situation awareness, and skill degradation. *Secondary evaluative criteria* consist of non-human performance-related consequences, such as costs of decision/action outcomes, which are important factors to determine the acceptability of the implemented automation. The three key factors described above for human-human collaboration fits in nicely as important primary and secondary evaluative criteria in this framework. In the following sections, key factors that influenced human-human collaborative behaviors in ATC environment are revisited to guide the design of future ATC decision support tools. Description and recommendations of future controller DSTs have been summarized in [12].

5.2 Responsibility and Control

In present-day ATC operations, the radar controller is fully in control and others assist him/her by either performing delegated tasks (e.g. hand-offs) or providing extra set of eyes to monitor the situation. Using shared knowledge of the situation, they work seamlessly together with minimal overt communication. Therefore, controller decision support tools for future ATC operations should provide similar assistance by either performing delegated tasks or providing advisories to the controllers. Many of the proposed ATC decision support tools provide functions that are analogous to those performed by radar associate and radar hand-off controllers. For example, automatic transfer-of-communication (TOC) via data link offloads tasks that are currently being performed by a controller. It is an ideal task for automation since it is generally workload intensive and congests radio frequency but are not safety critical. Other tools, such as conflict detection and speed advisories, assist the controllers to monitor the traffic and issue clearances that are optimized for efficient traffic flow [6,12].

Automated tasks that mimic the role of radar associates falls roughly under two categories: non-safety vs. safety critical tasks. Non-safety critical tasks have potential to be completely offloaded to the automation and/or another controller. Applying the automation design framework by Parasuraman, Sheridan, and Wickens, these tasks can be highly automated across the four stages – i.e. information acquisition, information analysis, decision/action selection, and action implementation – as long as there is a clear indication/feedback on when and where the automation is executing these tasks. For example, in the HITL studies [6,7], automated TOC was initiated by a manually transfer of the control of an aircraft from one sector to another. Therefore, controllers had a clear understanding as to when the TOC task was initiated. A clear understanding of the automated functions, along with an appropriate automation feedback to the controllers, resulted in a high acceptability of the automated TOC tools and procedures [6].

For safety critical tasks, however, the radar controller needs a greater control during the action implementation stage since s/he is directly responsible for any safety consequences of these actions. The responsibility of safe operations and the resulting consequences would be considered as secondary evaluative criteria under the design framework by Parasuraman, Sheridan, and Wickens [11]. Because people's lives are at stake, handling of the safety responsibility becomes a key factor behind the acceptability of any future ATC concept. Automation that supports safety critical functions should aid the controller with information acquisition and analysis but leave the actual decision/action selection and action implementation to the controller.

A similar division of labor already exists between the human operators. Radar associates are keenly aware of the workload constraints on radar controllers and are able to provide assistance at appropriate times with minimal intrusions to the radar controllers and their tasks. Similarly, automated conflict alert and advisories should also be sensitive to the controller workload constraints. They should be presented to the controller in such a way that the information is in the background until the controller chooses to access them. Tools that do not allow the controller to control when to access the information have had lower acceptance because of the frequent task interruptions that often increased the controller workload. For example, advisories that "pop up" on the screen without a controller action have shown to create significant increase in workload and display clutter.

5.3 Time, Workload, and Safety Constraints

Overall, it is inadvisable to delegate action implementations of safety critical tasks to the automation and relegate the controller to play a supervisory role. When tasks are delegated to automation, controllers have less situational awareness of the automated tasks. If automation cannot handle an off-nominal event for whatever reason and alerts the controller to resolve the problem, s/he is not likely to have enough time to gain sufficient situational awareness and resolve the problem, which can be catastrophic with safety critical events such as conflict resolution. This task infrastructure has an inherent problem since an early alerting by the automation increases the possibility of false alerts while late alerting gives the controller insufficient time to comprehend the situation and prevent mishaps. In an ATC environment, controllers need to be in the control loop of all tasks that are both time and safety critical at the cost of higher workload. Due to significant time, workload, and safety constraints, it will be a considerable challenge to design automation that will meet the primary evaluative criteria of positively impacting human performance via automation.

5.4 Shared Situational Awareness

When controllers use automation, they will be responsible for understanding the strengths and limitations of the automation to know when and how to use it in the operational context. Therefore it is important that the automation design supports the maintenance of controller's awareness of actions/intentions of the automated responses. However, in many human-automation interaction designs, much of the design is devoted to letting the automated system know the intentions of its human operators but little or no emphasis is placed on making sure that the human operator understands the actions of the automated system. Some aviation accidents are directly attributable to pilots who could not form accurate mental model of the situation due to complex automated systems actions that lacked proper feedback to the pilots [13].

Therefore, a key automation design consideration is that actions taken by the automation are transparently visible and understandable to the human operator. Although seemingly simple and obvious, this design rule may be difficult to achieve because of a mismatch between automation and human approaches to problem solving. The controller behaviors are based primarily on recognizing the kind of situation that is evolving in front of them and selecting appropriate actions from a set of heuristics that they have developed over many years of experience. Their ability to quickly recognize complex situations and assess them with respect to their base of relevant knowledge is critical to decision making in time pressured environment. This style of decision making has been referred to as a recognition-primed decision model [14].

In contrast, automation may rely on traffic geometry and other quantitative data to calculate probabilities of potential problems (e.g. conflicts) using mathematical algorithms. For example, a conflict detection algorithm may determine potential conflict based on time to conflict and its probability of occurrence, but human operators may have difficult time utilizing the probability value effectively in a time critical environment. Therefore it may be better to convert the probabilistic value into a deterministic one, such as simple yes/no answers based on a threshold probability value, even though this leads to mismatches between underlying algorithm and what is being conveyed to the controller. An effective communication is also necessary to make sure that all operators and automated systems have common shared intent. In human-human dialogue, the players make sure that they have arrived at a common understanding of the tasks by following acceptance, repetition, and confirmation procedures, which is needed for human-computer interaction as well [13].

6 Conclusions

Drawing analogies between human-human collaboration and human-computer interaction in today's complex systems is a sound approach, given increasing sophistication of automation that can adapt to human and situational needs. However, it is important to study the collaboration in a specific operational domain to apply to human-computer interaction in the same domain since each domain has situational constraints that makes certain collaboration styles more appropriate than others.

In ATC operations, some of the key factors that drive the collaborative behavior are 1) locus of responsibility and control, 2) time, safety, and workload constraints, and 3) shared situational awareness. This paper discusses how these factors affect feasibility/acceptability of future air traffic control concepts that changes human-human collaboration behaviors and how they should effect the development of future decision support tools. Real ATC systems are in fact much more complex than as they have been described in this paper. Multiple controllers within and between sectors collaborate with each other as well as with their decision support tools. They also collaborate with flight crews who also interact with flight deck automation tools concurrently. Together, air traffic control is truly a "system of systems" that merit ongoing research to fully understand the complex dynamics between human operators and computer systems.

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