Application of Communication Grounding Framework to Assess Effectiveness of Human-Automation Interface Design: A TCAS Case Study

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The role of the human operator in automation augmented domains has shifted from primary decision-maker to collaborative partner, where the human often has to understand and manage state changes that result from the automation itself. Due to the challenges of these progressively complex states, there is increasing demand for automation systems that provide effective human-automation interfaces that keep the human more “in-the-loop”. Effective human-automation interaction in this situation is akin to effective human-human communication: an effective conversation occurs when people use commonly understood verbal and non-verbal mechanisms that lead to shared understanding, or common ground. In this paper, we demonstrate how the application of a communication grounding framework, typically used to describe the practices of effective human communication, can be used as an analytic tool to assess human-automation interfaces. This analytic tool can be used to highlight design flaws likely to result in breakdowns in human-automation interaction, and ultimately lead to human error.

Aviation has been a strong domain for the advancement of automation. In the century since first flight in North Carolina, aviation has helped advance technologies in the domains of metallurgy, electronics, navigation and engine design. From the early days of the diminutive Wright Flyer, to the Airbus A380, aviation has been largely a successful collaboration of man with technology. However, the introduction of more, and increasingly sophisticated, automation into aircraft systems has not always gone as smoothly, or safely as intended. As aircraft designs have advanced, and begun to incorporate more complex automation systems, the pilot’s role has shifted from one of manual controller of the aircraft systems to a higher-level role of managing the various automation systems now controlling the aircraft systems, and if necessary, intervene in flight operations to respond to abnormal situations.

Pilots of modern aircraft must work collaboratively with the onboard automation systems to maintain efficient performance and safe operations. Unfortunately, this human-automation collaboration is not always successful. Several accidents investigated by aviation safety bodies have been attributed to ineffective human-automation interaction (AAIASB 1987). In many cases, the aircrew was unable to understand the message the automation was communicating. They failed to recognize the overall situation and instead dealt with a secondary condition of attempting to ascertain what the automation was trying to convey; a condition known as operator “Out-Of-The-Loop” (OOTL) syndrome (Endsley 1995). An example of this situation was the case of the fatal crash of Helios Airways flight 522 in August 2005.

Helios Airways 522 was a Boeing 737-400 on a charter flight from the island of Crete to Prague, Czech Republic. During the initial climb, the aircraft failed to pressurize due to a pressurization switch that had been left in the incorrect position. Subsequently, a warning horn had sounded identifying the condition. The crew failed to recognize the horn as dealing with a pressurization problem and misidentified the condition. The pilots, unaware of the now hypoxic environment, lost consciousness. The aircraft later crashed outside of Athens at the cost of 121 lives. The crash was attributed, at least in part, to the aircrew’s failure to successfully identify and interpret the aircraft warning systems activation (AAIASB 1987).

A challenge for automation designers is to ensure that their systems can effectively communicate warnings and alerts to pilots so that appropriate actions can be taken. In many automation systems, however, it is assumed that simply conveying the warning or alert message is sufficient for effective communication to occur, and for the problem to be resolved. For example, the crew alerting system (CAS) mentioned in the above example is designed to alert the pilot of abnormal conditions based on various aircraft parameters; however, it does not have the capacity to monitor the reaction of the pilots to any warning it conveys. Anyone who has ever sent directives via an email or written memo knows that simply conveying a message to someone does not necessarily guarantee that the recipient will understand the message and take appropriate action – even highly trained pilots. Messages can often be interpreted in multiple ways, depending on the context, and, thus, misunderstandings can occur. Experiences in
human-human communication show that successful communication typically requires much more interaction between parties, through an interactive back-and-forth process to establish that a message is understood (Clark and Brennan, 1991).

The inherent limitations of the one-way only communication model used in the CAS system has been recognized by automation designers, and more sophisticated alerting systems have begun to appear that incorporate improved communication processes that promote better human-automation collaboration. However, few analytic tools currently exist to assist designers in assessing how well their system designs promote effective human-automation interaction. Design limitations are often only discovered after expensive field testing has occurred or during accident investigations. Recognizing the parallels between human-human communication and human-automation interaction can open new possibilities for analytic tools, as one recognizes that decades of research has been dedicated to analyzing human communication processes and understanding how these processes can promote effective communication.

A particularly relevant communication analysis tool is Clark and Brennan’s (1991) communication grounding framework, as it describes the process by which people reach a mutual understanding or, common ground, when communicating. Such “grounding” is also critical in the aviation context, as pilots must clearly understand the message conveyed by an automation system in order to implement an appropriate response action. Grounding mechanisms identified by Clark and Brennan’s framework help communicating parties identify when misunderstandings have occurred, and help repair those misunderstandings. In the aviation context, it is important, for instance, that an automation system recognize when a pilot has misunderstood an alert and responded inappropriately, so that communication repairs can be made. In this paper, we show how the communication grounding framework can be used as an analysis tool to assess the effectiveness of the human-automation interaction processes enabled by the features of an automation system. We demonstrate this analysis method through a case study of a current aviation automation system, the Traffic Collision Avoidance System (TCAS).

To set the context for the case study, we first describe the TCAS automation system and then overview the communication grounding framework. Finally, we present the case study which analyzes the evolution of the TCAS design, and identifies how the design iterations introduced improved grounding mechanisms between the pilot and the automation system.

Traffic Collision Avoidance System (TCAS)

TCAS is an example of a device that warns pilots to the possible threat of collision with another aircraft. The system is a display situated in the flightdeck that is either a stand-alone device or one that is integrated with the navigation display. The display is comprised of an overview of the host aircraft as well as distance and relative altitudes of close proximity threat aircraft. If an aircraft enters a predefined range, the threat level of the aircraft is identified and registered on the display. In the application of TCAS to an impending collision scenario, time critical functions must be met with a response equal to the criticality of the scenario. This is accomplished by the use of aural and visual cues to increase the flightcrew’s awareness of the possible threat situation. In TCAS, levels of communication between automation and humans are divided into two classifications; either an information level or an immediate action response. The first state, known as a traffic advisory, deals with the possibility of an aircraft becoming a threat due to its close approximation to the host aircraft. As the threat aircraft approaches the subject aircraft, their indication on the host aircraft display will turn color from white to amber and an aural “traffic, traffic” alert will sound. The purpose of this message is to inform the pilots of potential threat traffic in close proximity to the host aircraft. If the threat aircraft continues to approach the threat aircraft, the system will provide an immediate action command, for example, a “Climb, Climb Now” (known as a resolution advisory), in case the pilots must execute in a expeditious manner.

The TCAS system is an example of an automation system that actively communicates to the pilot (human operator) across a two-way channel. The system recognizes actions undertaken by pilots at the direction of the resolution advocated by the particular warning system.

These warning systems were designed through an examination of the weaknesses of pilot response to environmental threats. In the time preceding TCAS, aircraft threat recognition and avoidance was primarily done through aural communication between pilots and ground controllers transmitting threat location relative to the
respondent aircraft, or between the pilots themselves via aural and non verbal gesturing (e.g., pointing to a certain location relative to their aircraft). After a long history of midair collisions, the United States Congress enacted legislation following the crash of Aeromexico flight 498 in August 1986 (NTSB, 2007) mandating that transport aircraft would require automated collision avoidance systems. In essence, the intent of the TCAS automation system is to augment both the communications between air traffic control and pilots and between the flightcrew themselves with another aid in collision detection and avoidance.

Initial TCAS technology provided for very few states. The original system (TCAS I) informed the pilots of a potential threat (the aural “traffic” call with accompanying visual display) and a “Clear of Conflict” aural presentation. The original TCAS system did not have the capacity to understand if the message was interpreted correctly by the pilots and had no provision to update or revise the message if the pilots failed to understand the original message. TCAS I provided the same type of one-way communication model as the original CAS technology, and failed to advance the need for confirmation of understanding of the intended message. The case study will discuss this design limitation in more detail and how the revised TCAS II system addressed this design issue.

Clark and Brennan’s Communication Grounding Framework

Clark and Brennan’s (1991) theory of communication grounding is one of the most fundamental and influential theories and frameworks to arise from the human communication literature. It has been widely used by communication and collaboration researchers to understand human communication behavior (e.g., Stahl, 2006), as well as an analytic tool to assess the ability of collaboration technologies to support successful communication (e.g., Vandergriff, 2006, Beers et al., 2007). Clark and Brennan’s work has primarily been applied to the exchange of information between humans; however, researchers have previously utilized it to examine interaction between autonomous systems. Billard and Dautenhahn (1998) examined the use of common ground in the education of autonomous robots; specifically to examine information exchange between student and teacher robots.

The fundamental concept underlying the communication grounding framework is that effective communication relies on people’s ability to reach a mutual understanding, or common ground, of the messages being conveyed to one another during a conversation. Reach this common ground, often referred to as “being on the same page”, is accomplished through a process called grounding (Clark and Brennan, 1991). A core component of the grounding process is that conversation proceeds in a series of presentation and acceptance phases (Figure 1), during which the conversing parties attempt to achieve a mutual understanding of the message conveyed (or presented) before moving onto the next presentation and acceptance conversational segment.

**Presentation phase:** A presents a message to B

**Acceptance phase:** B accepts the message by giving evidence that he/she believes what A means by that message.

![Figure 1. Conversational segment (Clark and Brennan, 1991)](image)

The grounding process begins, and is a key aspect of, the acceptance phase. The message receiver, B in Figure 1, attempts to determine whether she understands the message that the presenter, A in Figure 1, has conveyed. If B believes she does not understand the message she will provide negative evidence of grounding by requesting clarification from A, or providing a similar response. If B believes she understands the message, but in fact does not, A will monitor B’s response during the acceptance phase (and, in fact, throughout the rest of the conversation) for any evidence of a misunderstanding. If such evidence presents itself, then A will attempt to repair the miscommunication in order to complete the acceptance phase.

The communication grounding framework describes several forms of evidence people use to assess whether grounding has been achieved. The most common, and most relevant for our purposes include:

- **Lack of negative evidence**, i.e., evidence one was misheard or misunderstood
- **Relevant next turn**, e.g., receiving an appropriate answer to a question
In the human-automation communication context, an example of a relevant next turn would be for a pilot to implement an appropriate action in response to an automation alert, and thereby providing positive evidence to the automation system (if it is capable of monitoring the pilot’s actions) that the alert was understood correctly. If instead, the pilot took no action when needed or an incorrect action this would provide negative evidence of grounding, which the automation system could then identify and respond to in order to clarify the original message (and complete the acceptance phase of grounding).

Measuring the degree of successful automation, from the communication grounding framework perspective, in human-automation interactions should answer the following questions: Is the message clearly conveyed? Has the message been understood and accepted by the receiver. If not, does the receiver have the ability to tell the original sender if the message is not understood? Does the original sender have the capacity to revise that original message in order to repair the misunderstanding?

Another fundamental concept of communication grounding is the principle of least collaborative effort: “In conversation, the participants try to minimize their collaborative effort – the work that both have to do from the initiation of each contribution to its mutual acceptance.” (Clark and Brennan, 1991). This principle dictates that people will work together to minimize the overall effort expended during a conversation. On one hand this means that participants will attempt to minimize their own personal effort in transmitting and receiving information. On the other hand, it also establishes a social contract between parties to help each other efficiently reach a mutual understanding. In essence, this means that the “receiver” of the information will not make the “sender” do all the work to convey a clear and precise message. The receiver will help the sender by identifying misunderstandings, and perhaps even suggesting alternative messages for the sender to consider to repair misunderstandings should they occur. This is a highly interactive process, but allows people to communicate very efficiently overall.

In the aviation context, brief alert messages are typically preferred, for example, the aural warning message “traffic”, is typically used over a more elaborate, but unnecessary, “another aircraft in close proximity to you”. Likewise, instead of requiring a pilot to acknowledge the “traffic” alert via input into the system before taking action, simply responding with the appropriate action will provide positive evidence of understanding and minimizes overall communication effort between the human and the automation.

The presentation and acceptance phases of a conversation have their own associated challenges unique to the medium in which they are taking place. For example, a face-to-face conversation requires less mental taxation than that of a text conversation from distant participants. These challenges, or constraints, are one of the dimensions that affect grounding. They are the basis by which parties increase overall performance through different environmental conditions. If augmentation of these dimensions can be achieved, the reduction of collaborative effort would be the overall outcome. These constraints include, but are not restricted to (Clark and Brennan, 1991):

- **Visibility**, an environment in which A and B are visible to each other.
- **Audibility**, an environment in which A and B can hear each other.
- **Reviewability**, an environment / media in which B can review A’s messages.

Costs, on the other hand, provide alternative measures to address weaknesses in constraints. The penalty for these costs can retard the effective communication between communication participants. Communication costs include, but are not restricted to (Clark and Brennan, 1991):

- **Reception costs** are associated with receiving a message. Listening is generally easier (lower cost) than reading.
- **Understanding costs** are associated with understanding a message. The more complex the message or words used to convey the message, the higher the understanding cost.
- **Start-Up costs** are associated with initiating a communication. When co-present, start-up costs tend to be low, except if the environment is chaotic, and then getting the receiver’s attention may be costly.

Automation designers must be aware of the potential constraints and costs associated with their system design and with the environment in which the system will be deployed. Each of these factors can influence the ability of the system to support effective grounding during human-automation interaction.
Case Study

The introduction of the initial TCAS I traffic warning system provided a significant advancement in collision avoidance, certainly above the historical “look out the window” approach. Analyzing the TCAS I design using the communication grounding framework, however, reveals limitations in its ability to support effective communication between the automation and the flightcrew. When a threat aircraft is recognized, the TCAS I system communicates this threat by presenting the relevant information to the flightcrew in both aural and visual formats; in this case an amber target is displayed on the TCAS display and an aural “Traffic, Traffic” message is provided. This is the “presentation phase” of the communication between the automation and the pilot. In human-human communication, this phase would then be followed by an “acceptance phase”, during which the message receiver would demonstrate to the message conveyer that they have understood the message and the conveyer would monitor the receiver’s behavior for evidence of understanding. The TCAS I system enables only a limited type of acceptance phase; it only monitors for positive grounding evidence, indicated by the pilots implementing the appropriate maneuver away from the threat aircraft. Once a positive outcome is detected, the TCAS I system would issue the aural message “Clear of Conflict”. While this represents one type of “presentation” and “acceptance” phase, the grounding framework demonstrates that other grounding mechanisms are often necessary to facilitate successful communication after an initial message is presented.

From a grounding perspective, the main limitation of TCAS I is that it cannot detect miscommunications, and consequently, cannot attempt to repair those miscommunications. There is no provision in the system to monitor the flightcrew’s actions for negative evidence of grounding (e.g., no action or an incorrect action taken). Thus, TCAS I has no means to repair a miscommunication, through, for example a revised cautionary command that might facilitate a relevant next turn by a flightcrew who has misinterpreted the significance of the initial presentation.

The revised TCAS II system addresses some of these issues by providing more sophisticated communication possibilities between the automation and the flightcrew after the initial presentation of the traffic advisory warning message (“Traffic, Traffic”). Once the initial warning is issued, TCAS II monitors the flightcrew’s actions for evidence of grounding. In particular, it can recognize whether actions have been taken to maneuver the aircraft away from the threat, and whether these actions will be sufficient. If not, TCAS II can revise the initial message with the resolution advisory, or RA (“Climb, Climb Now”), in order to repair the miscommunication. The manner in which this message is conveyed also facilitates grounding. The brief aural command minimizes reception costs (listening to a warning is easier than reading a display) and understanding costs (the short climb command is easier and less time restrictive than detailing the action for the aircraft to increase altitude). Also, the ‘climb’ directive is also visualized on the TCAS display, providing reviewability, which further reduces understanding costs (visibility and audibility versus audibility alone). If the TCAS II system determines that the rate of climb or descent is insufficient after issuing an RA to the flightcrew, an aural “Adjust Vertical Speed, Adjust” will be broadcast. As with TCAS I, the communication loop is closed with the “Clear of Conflict” acceptance message.

Overall, the revised TCAS II design provides a much more interactive communication process between the automation system and the flightcrew, more closely aligned with human-human communication, primarily through expanded monitoring and communication repair capabilities in the automation design. Miscommunications are recognized and repaired to achieve a positive overall outcome.

In summary, TCAS II expands on the initial presentation / acceptance framework in TCAS I by introducing the ability of TCAS II to revise miscommunications. TCAS II provides for the automation to look for positive and negative evidence of grounding from the flightcrew that the initial presentation has been accepted and understood.

Challenges Looking Forward

Although the design revisions introduced in the TCAS II system provided expanded communication potential for human-automation interaction, its grounding capabilities could be improved. A recent traffic safety study by Eurocontrol (2010) identified key shortcomings in the TCAS II system. The most prominent failings identified in the study related to the system’s inability of revise a resolution advisory in order to resolve a potential collision. From a grounding perspective, this indicates the system’s inability to recognize a wider variety of negative evidence from the flightcrew’s actions.
In the case of the traffic advisory, negative evidence occurs when no actions are taken in response to the initial presentation of the warning. In the TCAS I system, there was no ability to repair this miscommunication. TCAS II addressed this challenge with the RA (“Climb, Climb Now”) command. The new challenge occurs while the aircraft is following an RA. When in RA mode, repairs must address not only the performance of the host aircraft (whether or not to climb or descent) but also the degree of execution. Although this is evident with the “Adjust Vertical Speed, Adjust”, the repair message is not explicit enough as to whether the adjustment should be more or less aggressive, potentially introducing more misunderstanding. The performance profile is currently only included on the TCAS display. A message that more explicitly indicates these factors would facilitate the grounding process. The result would be a decrease in the understanding costs and a net positive performance.

The Eurocontrol study also identified the need for an RA reversal (e.g., from climb to descent) if the actions of the threat aircraft contravene its own TCAS system. This capability would require further design changes to the TCAS system to enable the presentation of a new, alternative message to the flightcrew, and further monitoring of the crew’s understanding of this new message.

Conclusion

The effort to formulate messages in human-human conversations shared a close association with human-automation interaction. In this paper we examined how theories that were once identified as constituting the minutia of human-human conversations can be applied to human-automation communication. By examining the communication grounding framework, we identified this as an analytic tool to help designers assess the effectiveness of their automation system for promoting effective human-automation communication. The presented case study on the TCAS automation system highlights and explains crucial design improvements that contribute to improved human-automation communication in the current TCAS II system. The communication ground framework also helped identify design deficiencies that were addressed in proposed TCAS display improvements.

References


