Properties for formally assessing the performance level of human-human collaborative procedures with miscommunications and erroneous human behavior

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1. Introduction

With the development of industrial technology, safety-critical systems in nuclear power plants (NPP), the chemical process industry, and air transportation have become more complex. As such, their safe operation depends not only on the individual skills and knowledge or human operators, but also effective and efficient team communication and collaboration. In these sensitive systems, failures can be associated with the erroneous behavior of individual human operators (Reason, 1990) as well as human-human collaboration. For example, it is reported that in Germany, communication errors are responsible for about 10% of the workplace incidents resulting from human error (Sträter, 2003).

Of particular interest to this work is the main control room (MCR) of nuclear power plants (NPPs), where communications and collaboration among operators are essential factors for understanding how and how well MCR operators deal with abnormal or emergency situations. In particular, the performance of MCR crew under abnormal/emergency situations in NPPs is strongly affected not only by operators’ cognitive processes, but also by communication and collaboration among operators. Communication error has been considered as one of the main causes of accidents and incidents in NPPs. Hirotsu et al. (2001) reported that in Japanese
NPPs, 25% of human error incidents were due to communication failure. Stratér (2003) investigated 232 operational events involving human error in German NPPs and found that roughly 10% of them involved human errors mainly caused by communication problems. Similar results have been observed in ground transportation (Murphy, 2001), medicine (Wilson et al., 1995), and aviation (Connell, 1996).

From these investigations and analyses, we can conclude that maintaining reliable communication and human behavior is essential to secure the safety of large, complex systems. If team members could perform and collaborate better, the safety of many systems would be improved. So far, standard human-human collaborative procedures and communication protocols have been used to ensure effective and efficient collaboration in many safety-critical systems. For example, operation crews in MCR of nuclear power plants use communication protocols to diagnose problems and execute emergency operations (Kim et al., 2010). However, there is concurrency between human operators and parts of procedures. The concurrency creates complexity and thus potentially induces unanticipated interactions between operators. Further, humans are fallible. They can perform protocols erroneously by incorrectly performing their parts of the procedure or by miscommunicating information to team members. Therefore, it can be difficult to evaluate the safety of human-human collaborative procedures using conventional analyses methods, like experimentation and simulation that can miss unexpected conditions and interactions.

Formal methods offer proof-based analysis techniques capable of considering all possible interactions. While formal methods have been used to evaluate machine communication protocols, the existing approaches (Bochmann and Sunshine, 1980; Sidhu and Leung, 1989) are ill-suited for use with human-human collaborative procedures for several reasons. First, humans behave in different ways from machines. Humans follow tasks as opposed to machine code and human-human communication must be contextualized as part of a task (Traum and Dillenbourg, 1996). Second, humans are more flexible than machines and are thus fallible in different ways. Third, human collaborative procedures are inherently less fragile than machine communication protocols because of the looser dynamics of human-human communication. As such, the outcome of human-human collaboration may represent. There are a variety of temporal and modal logics that have been used to express specifications. The most common one, and the one used in the presented work, is linear temporal logic (LTL) (Emerson, 1990). LTL allows one to reason about the relationship between different states and/or variables over ordinal time and assert properties about all of the paths through a model. It does this using model variables; basic Boolean logic operators including $\land$, $\lor$, $\neg$, $\Rightarrow$, and $\epsilon$; and temporal operators (Table 1).

While formal methods have traditionally been used in the analysis of computer hardware and software systems, a growing body of work has been investigating how to use them to evaluate human factors issues (Bolton et al., 2013). However, when it comes to issues of human-human communication and coordination, there has been very little work. The Concur Task Trees formalism (Paternò et al., 1997) has been extended to allow for the modeling of human-human coordination and communication, where communications could have different modalities (synchronous or asynchronous, point-to-point, or broadcast), and used to formally evaluate pilot and air traffic control radio communications during runway operations using different shared task representations (Paternò et al., 1998). Although this method is useful, it did not easily distinguish between separate and shared operator tasks, nor did it account for potential miscommunications and operator perceptual or cognitive errors. Both limitations were addressed by the Enhanced Operator Function Model with Communications (EOFMC).

<table>
<thead>
<tr>
<th>Name</th>
<th>Operator</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>$C \psi$</td>
<td>$\psi$ will always be true.</td>
</tr>
<tr>
<td>Next</td>
<td>$X \psi$</td>
<td>$\psi$ will be true in all next states.</td>
</tr>
<tr>
<td>Future</td>
<td>$F \psi$</td>
<td>$\psi$ will eventually be true.</td>
</tr>
<tr>
<td>Until</td>
<td>$\psi \mathcal{U} \Psi$</td>
<td>$\psi$ will be true until $\Psi$ is true.</td>
</tr>
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