Research on Verification for STPA-Based Avionic System Software Safety

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Abstract. Software safety problems resulting from relevant faults are increasingly highlighted as systems become more and more complex. Thus, the static verification method is inapplicable to complex system. This paper adopts System-Theoretic Process Analysis (STPA) to identify hazards in system, and obtain software-relevant safety needs. Safety verification adapting for complex system is clarified with the combination of STPA and model test software safety analysis and verification. Analysis and research adopting STPA method are conducted and their feasibility are proved.

1. Introduction

The importance of software safety is becoming more and more serious with the complexity of the system. Many safety problems, even casualties are caused by software faults. Code errors are not the only reason for these accidents. Software incompletion and other faults are also responsible for the loss. Therefore, software safety is a systematic problem, which must be solved with systematic ways. STPA\(^[1]\) served for this way, which emphasizes component deficiency and hazards resulting from interactions of parts of the system.

2. Verification Method for STPA-Based Software Safety

2.1 STPA

STPA, a danger analysis technology derived from Accident Causality Model Based on System Theory (STAMP), deals with safety problems systematically. STPA can be applied in the early phase of system development, or before designations of advance safety needs and restrictions. Compared with traditional safety analysis technology based on reliability, STPA has more strengths on identifying scenarios of multi-factors and dangers. In terms of software, STPA is aimed to recognize insufficient controls which may lead to dangers, and to ensure relevant safety restrictions on acceptable risks. Besides, relevant information concerning violations of safety restrictions can be obtained. These information can be adopted to control, decrease and eliminate dangers in the system designation and processing \(^[2]\).

2.2 Comparison Between Different Methods

Currently, common software safety analysis and verification technology consists of Preliminary Hazard Analysis (PHA)\(^[3]\), Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA). These technologies analyze and verify software safety from different angles and ways. However, they all have limitations respectively.

Firstly, PHA is based on engineering experience data base, without which would lower the performance of PHA. FTA is driven by events. It is impossible to define certain event and derive unified results by applying FTA because of the large amounts of events, complex logic relations and interactions of events in weapon system software. FMEA suits for pure software function analysis. Thus system safety restrictions are hard to derive. Secondly, preconditions for traditional software safety analysis and verification method are based on components failures. For the safety of software,
analysis are conducted after the designation of software. These cannot basically meet the demands of complex software safety analysis.

Compared with traditional ways, STPA, an iteration way, can analyze software safety with the combination of satisfying advanced system, safety restrictions and system analysis without using complete engineering experience database [4], never be apart from process and system. Therefore, STPA can guarantee software safety better when applying to complex weapon system.

Table 1. Comparison between the Four Methods

<table>
<thead>
<tr>
<th>name</th>
<th>Scope of application</th>
<th>Applicable state</th>
</tr>
</thead>
<tbody>
<tr>
<td>STPA</td>
<td>No need for complete engineering experience data base</td>
<td>Dynamic iterative</td>
</tr>
<tr>
<td>PHA</td>
<td>Based on engineering experience data base</td>
<td>static</td>
</tr>
<tr>
<td>FTA</td>
<td>Event-driven, applicable to simple interactive system</td>
<td>static</td>
</tr>
<tr>
<td>FMEA</td>
<td>Applicable to pure software function analysis, hard to derive system safety restrictions</td>
<td>static</td>
</tr>
</tbody>
</table>

3. Verification Procedures for STPA-Based Software Safety

Normally, software verification is designed for proving correctness of functions [5] and whether software can meet demands of overall functions. However, software safety cannot be guaranteed by only verifying software correctness. Thus, it is essential to conduct analysis on software safety and to verify it accordingly [6].

Whether the software suits or satisfy safety restrictions is the presupposition of safety verification [7]. Safety verification is different from function verification. The former aims to guarantee software safety by applying safety analysis results; the latter software functions [8].

Verification for STPA-based software safety is conducted as Figure 1:

![Figure 1. Verification procedures for STPA-based software safety](image)

Obtaining software safety requests from system

Regularization for safety requests and restrictions

Obtaining code-leveled safety verification

Step 1 Obtaining software safety requests from system

This procedure is designed for conducting software analysis in system, and for identifying potential software hazards which may lead to accidents. As it is showed in the following steps:

1. Identify all potentially hazardous software control measures;
2. Evaluate whether each CA has four kinds of normal-type hazardous behavior so as to identifying Unsafty (UCAs): (1) not providing CA; (2) providing UCA; (3) over early, over late, or unqualified potential CA; (4) early halt or over lasted CA.
3. Transform the definite UCAs to informal text software safety requests (SSR);
4. Understand how each UCAs occurs by using process model and its variables;
5. Clarify each combination of process model variables of UCAs. Evaluate each combination in \( C_i=\text{providing CA or no providing CA} \). Make it clear whether CA is under hazard in respective environment.

Note: CA can be considered as hazardous in system if combination of process variables are only relevant to CA and cause system-leveled hazard \( H_i \in HZ \)
(6) Improve software safety by applying Boolean operator V and Λ using results derived from step 5.

Note: The output of this step is a table of relevant software safety requests. Each software safety requests \(SSR_{ij}\) has a \(UCA_{ij}\) counterpart. \(i\) stands for the serial number of CA, while \(j\) quantity of UCAs.

Definition 1:
Define \(PMV_{ij}=\bigcup (P_{i,1}, \ldots, P_{i,n})\) as the set of process model variables relevant to \(CA_i\), leading to hazard \(i \in \mathcal{H}, C_i=\{providing CA\} \lor C_i=\{not providing CA\}\), \(n\) stands for the maximum quantity of relevant variables. \(Ω\) is the combination of \(PMV_{ij}\) values. Thus \(SSR_{ij}\) can be represented as follows:

\[
SSR_{ij}=(ΩPMV_{ij}→CA_i) \lor SSR_{ij}=(ΩPMV_{ij}→¬CA_i)
\] (1)

This means \(CA_i\) is not available in \(PMV_{ij}\) combination \(Ω\) value.

Procedure 2: regularization of safety request and restriction

Clarify the safety request. Linear-time temporal logic (LTL) must be applied to formalize these safety requests so as to verifying them in the next step. These requests can be reflected to the formalization of LTL for verification through model check if relevant software safety requests are identified and presented by using Boolean operator. LTL formula can be defined in a set of atomic assumption, Boolean operator (¬, V, Λ, ↔, →, true, false) and time operator (next, always, eventually, U until, R release). Safety requests make sure no hazardous behavior occurs in the process of conducting.

Definition 2:
Take \(SSR_{ij}\) as software safety request, all software execution route must be like this from the beginning to the end. Thus \(SSR_{ij}\) LTL formula is as follows:

\[
φ=□(SSR_{ij})
\] (2)

in which

\[
SSR_{ij}=(ΩPMV_{ij}→CA_i) \lor SSR_{ij}=(ΩPMV_{ij}→¬CA_i)
\]

□ represents all status of executive route.

This formula means the emergence of \(PMV_{ij}\) will always cause the fact that software must (or cannot) provide \(CA_i\), i.e.:

\[
φ=□(PMV_{ij}→CA_i) \lor φ=□(PMV_{ij}→¬CA_i)
\] (3)

According to the above definition, safety request defined by safety analysis can be easily transformed into LTL.

Procedure 3: obtaining code-leveled safety verification

Based on procedure 2, this procedure is designed for regularization of code-leveled safety request verification. This procedure can be accomplished through two different ways: 1. conducting formal verification by using model inspector [9]; or 2. Generating 3 test samples by using model inspector. Model inspector take software model and relevant quality as input, and write into time logic, then test the overall status space effectively.

4. Real Example of Avionic System

Take Avionic equipment operating system software for research example in order to analyze safety request for software system structure design. Avionic system, an essential part of modern aircraft, is closely related to aircraft combat performance. It is reported that avionic system failure may cause catastrophes even casualties. Normally, operating system of avionic equipment must meet needs of hundreds of safety requests. Table II shows safety request subset in research example of avionic equipment operating system.
### Table 2. Safety request subset in research example of avionic equipment operating system.

<table>
<thead>
<tr>
<th>Request subset</th>
<th>Illustration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Display aircraft altitude data</td>
<td>Altitude data here is defined as aircraft altitude above the sea level.</td>
</tr>
<tr>
<td></td>
<td>Altitude data is applied to ground collision test system. Pilot needs to</td>
</tr>
<tr>
<td></td>
<td>pay attention to altitude data.</td>
</tr>
<tr>
<td>Display aircraft position data</td>
<td>Position data here refers to aircraft longitude and latitude coordinates</td>
</tr>
<tr>
<td></td>
<td>received from GPS. Aircraft position data is displayed together with</td>
</tr>
<tr>
<td></td>
<td>other points. Pilot can watch the route deviation and take actions</td>
</tr>
<tr>
<td></td>
<td>according to it.</td>
</tr>
<tr>
<td>Display aircraft gyro data</td>
<td>Gyro data refers to the relative orientation of the airplane annex with</td>
</tr>
<tr>
<td></td>
<td>respect to ground angles, including pitch angle, yaw angle and roll angle.</td>
</tr>
<tr>
<td>Display fuel data</td>
<td>Fuel quantity refers to the overall quantity of fuel available in aircraft</td>
</tr>
<tr>
<td></td>
<td>fuel tank.</td>
</tr>
</tbody>
</table>

UML graph can be adopted to illustrate above issues as it is showed in Graph 2. Generally speaking, the operating system of avionic equipment consists of display system G, platform system P and navigation system N. G is for receiving aircraft fuel data (Fuel) provided by fuel sensor; N altitude data (Alti), aircraft gyro data (Gyro) and aircraft position data (GPS), provided by altitude meter, gyroscope and GPS respectively; G displaying P, C, N. G1 and G2 read and display aircraft altitude, attitude, position and fuel.

![UML graph for relations between operating system of avionic equipment](image)

Figure 2. UML graph for relations between operating system of avionic equipment

Lists factors that may cause hazards (HZ). Software safety focus on those hazard-causing defaults and relevant design bugs and exterior input conditions [10,11]. From $HZ_1$ to $HZ_4$, these factors is proved to be disastrous, leading to air crash. For example, pilot judgments to altitude are interfered with incorrect altitude data, causing ground collision, air crash, casualties, system loss and damages to environment.

### Table 3. Hazard identification in case research

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Code name</th>
<th>Hazard</th>
<th>Possible Reasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HZ1</td>
<td>Display false altitude data</td>
<td>Altitude meter data loss or fault, disconnection or false connection to altitude meter, display errors.</td>
</tr>
<tr>
<td>2</td>
<td>HZ2</td>
<td>Display false position data</td>
<td>GPS data loss or fault, disconnection or false connection to GPS, display errors</td>
</tr>
<tr>
<td>3</td>
<td>HZ3</td>
<td>Display false gyro data</td>
<td>Gyroscope data loss or fault, false connection to gyroscope, display errors</td>
</tr>
<tr>
<td>4</td>
<td>HZ4</td>
<td>Display false fuel quantity</td>
<td>Fuel sensor data loss or fault, false disconnection or false connection to fuel sensor, display errors.</td>
</tr>
</tbody>
</table>

(1) Software CA: avionic system software has 4 CAs. The operation for each CA depends on four kinds of records of general hazard type.
UCA1.1: one data loss or fault; UCA1.2: connection time and sequence fault; UCA1.3: data displaying stops on certain readings.

(2) UCA: Evaluate each item mentioned above, and check reasons which cause hazard. If the item is hazardous, relevant HZ should be distributed for system-leveled hazard, vice versa.

(3) Advanced safety request: Each UCA will be transformed into relevant safety restriction. Table IV shows relevant safety restrictions of UCA.

<table>
<thead>
<tr>
<th>Related UCAs</th>
<th>The corresponding security constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCA1.1</td>
<td>SSR$_{1.1}$ no altitude, position, gyro, and fuel data loss and correct</td>
</tr>
<tr>
<td></td>
<td>no connection time and sequence delay</td>
</tr>
<tr>
<td>UCA1.2</td>
<td>dynamic and real-time changing data displaying</td>
</tr>
</tbody>
</table>

4) Process model variables: process model variables mainly include fuel monitor, Gyro monitor, GPS monitor, Alti monitor, graphics monitor, plane state.

5) Analyzing causes of UCAs

<table>
<thead>
<tr>
<th>Control measures</th>
<th>Process model variables</th>
<th>Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel$_{\text{monitor}}$</td>
<td></td>
</tr>
<tr>
<td>Aircraft State</td>
<td>Gyro$_{\text{monitor}}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GPS$_{\text{monitor}}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alti$_{\text{monitor}}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Graphics$_{\text{monitor}}$</td>
<td>CA</td>
</tr>
<tr>
<td></td>
<td>CA$_{1}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>providing</td>
<td>UCA1.1</td>
</tr>
<tr>
<td></td>
<td>True</td>
<td>False</td>
</tr>
<tr>
<td></td>
<td>True</td>
<td>True</td>
</tr>
<tr>
<td></td>
<td>True</td>
<td>True</td>
</tr>
</tbody>
</table>

6) Construct relevant safety request: 

$$SSR_{1.1} = \Box (PMV_{1.1} \rightarrow \neg CA_{1})$$  (4)

in which $PMV_{1.1} = P_{1.1} \land P_{1.2} \land P_{1.3}$

$P_{1.1} = ([Fuel_{\text{monitor}} \lor Gyro_{\text{monitor}} \lor GPS_{\text{monitor}} \lor Alti_{\text{monitor}} \lor Graphics_{\text{monitor}}] = false);$

$P_{1.2} = [Graphics_{\text{monitor}} = false];$

$P_{1.3} = [Graphics_{\text{monitor}} = null];$

$CA_{1} = true$

According to Definition 2, map system-leveled STPA software safety request as formal format in LTL. The formal format of LTL software safety request can be sampled as follows:

$$SSR_{1.1} = \Box (Fuel_{\text{monitor}} \land Gyro_{\text{monitor}} \land GPS_{\text{monitor}} \land Alti_{\text{monitor}} \land Graphics_{\text{monitor}}) = false \rightarrow \neg(\text{plane}_\text{state});$$  (5)

$$SSR_{1.2} = \Box (Graphics_{\text{monitor}} = false) \rightarrow \neg(\text{plane}_\text{state});$$  (6)

$$SSR_{1.3} = \Box (Graphics_{\text{monitor}} = \text{null}) \rightarrow \neg(\text{plane}_\text{state});$$  (7)

By adopting SPEC-test program, verification requests of system model and tense logic formula presented by module code are illustrated as follows. In it, plane-state , an enum type, has 2 values: normal and abnormal.

SPEC

G((Fuel$_{\text{monitor}}$ & & Gyro$_{\text{monitor}}$ & & GPS$_{\text{monitor}}$ & & Alti$_{\text{monitor}}$ & & Graphics$_{\text{monitor}}$)==false}
5. Summary

Given that traditional software safety can hardly be adapted to complex system safety analysis and verification, this paper conducted system hazard analysis applying STPA and derived software relevant safety request in the background of avionic system. Mapping those software-related safety requests as formal logic formula and verifying their code-leveled safety provide referential experience for further the application of STPA to weaponry and equipment. However, analysis process depends on artificial analysis. Automatic tools and ways are in the further development list.

References

[6]. Black, P.E.: Test Generation Using Model Checking and Specification Mutation. IT Professional 2014.16(2), 17–21