The Role of Self-Forensics in Vehicle Crash Investigations and Event Reconstruction

Serguei A. Mokhov
Department of Computer Science and Software Engineering
Concordia University, Montreal, Canada
mokhov@cse.concordia.ca

Abstract

This paper further introduces and formalizes a novel concept of self-forensics for automotive vehicles, specified in the Forensic Lucid language. We argue that self-forensics, with the forensics taken out of the cybercrime domain, is applicable to “self-dissection” of intelligent vehicles and hardware systems for automated incident and anomaly analysis and event reconstruction by the software with or without the aid of the engineering teams in a variety of forensic scenarios. We propose a formal design, requirements, and specification of the self-forensic enabled units (similar to blackboxes) in vehicles that will help investigation of incidents and also automated reasoning and verification of theories along with the events reconstruction in a formal model. We argue such an analysis is beneficial to improve the safety of the passengers and their vehicles, like the airline industry does for planes.

Keywords: self-forensics, specification, Forensic Lucid, event reconstruction, forensic computing, autonomic computing

1 Introduction

In this work we apply a novel concept of self-forensics to vehicle design allowing vehicle’s subsystems to analyze themselves forensically as needed and preserve the forensics data for further automated analysis in the cases of failures, crash, and event reconstruction.

We insist this should be a part of the protocol for for each new vehicle design, to monitor its hardware and software components.

Problem Statement. It may become relatively difficult-to-impossible to do event reconstruction in testing and crash incident analysis e.g. to determine a faulty component or any other internal cause of crash if a vehicle in question is badly damaged. Even if some of information may be available at the incident scene to the investigators, including eyewitness stories and the actual final state of the vehicle, it may never be clear what was the reason (other than the external evidence), so ad-hoc conclusions can be incorrectly inferred from what the investigators can see as well as the eyewitness stories of the exterior to the accident.

Proposed Solution. We propose to include a notion of self-forensic components included into the hardware and software design of the modern cars. Their purpose is multi-fold. They can serve as the real-time monitoring and logging and analyzing subsystems of critical vehicle parts and overall health as well as measuring parameters such as as speed, temperature, etc. over safety-predefined thresholds in a durable blackbox-like device in a Forensic Lucid format (with a possibility of external export via wireless communication) with the intent of in-situ automatic analysis and reasoning response as well as for after-the-fact for the purpose of event reconstruction to be complete based on the self-forensics journals automatically with tools making sure no event is missed and the analysis is thorough. The approach, combined with an expert system, can also be used to train personnel in such investigative techniques. It would also allow to pin-point a potential cause of the fault inside rather than external allowing to more precisely hold someone accountable.
Organization. First, we introduce the notion of forensic computing, the Forensic Lucid language, the self-management properties of autonomous systems, etc. as a background and the related work to give the reader the idea for this work in Section 2. Then we overview the notion of self-forensics Section 3 and its application to the vehicle safety design with the purpose of automated reasoning during the activity as well as preservation of the evidential data for later analysis and event reconstruction using automated tools. We go over requirements, limitations, advantages and examples. Then, we conclude and present some future work items in Section 4.

2 Background and Related Work

2.1 Forensic Computing

The notion of computer forensics also known as cyberforensics or the associated forensic computing has been traditionally associated with computer crime incidents investigations [1, 2]. We show the approach is useful in vehicle crash investigations and event reconstruction.

Further we argue if the new technologies are built with the self-forensics software and hardware toolkits or components, it would even help the automotive industry to improve the safety design of the vehicles and implement decision-making modules when real-time event analysis may lead to catastrophic or similar outcomes or during crash testing of new vehicles.

The notion of self-forensics was first proposed by Mokhov [3] for autonomous systems such as NASA spacecraft as well as large- and medium-scale distributed software systems that need to support themselves and analyze themselves with the new self-forensics autonomic property.

2.2 Self-Management Properties

The notion of self-management and self-managed systems comes from autonomic computing (AC) [4, 5]. The common aspects of self-managing systems, such as self-healing, self-protection, self-optimization, self-configuration and the like are now fairly well understood in the literature and R&D [6, 7, 8, 9, 10].

We formally introduce another autonomic property that we call self-forensics that we would like to be a part of the standard specification for vehicle systems specification.

2.3 Forensic Lucid

Forensic Lucid [11, 12, 13] is a forensic case specification programming language for automatic deduction and event reconstruction of computer crime incidents. The language itself is general enough to specify any events, their properties, duration, as well as the context-aware system model. We take out Forensic Lucid from the cybercrime domain for its eventual application to aid the vehicle crash incidents investigation from within as an example of self-forensic case specification.

Forensic Lucid is based on the Lucid [14, 15, 16, 17, 18] language and its various dialects that allow natural expression of various phenomena, inherently parallel, and most importantly, context-aware, i.e. the notion of context is specified as a first-class value in Lucid [19, 20, 21]. Lucid dialects are functional programming languages. All these properties make Forensic Lucid an interesting choice for forensic contextual logging and computing in crash investigations related to the internal failures of the components.

Forensic Lucid is also significantly influenced by and is meant to be a usable improvement of the work of Gladyshev et al. on formal forensic analysis and event reconstruction using finite state automate (FSA) to model incidents and reason about them [22, 23].
While Forensic Lucid itself is still being finalized as a part of the PhD work of the author along with its compiler, run-time and development environments, and the accompanying expert system, it is well under way to validate its applicability to various use-cases and scenarios [13, 24].

Context

Forensic Lucid is context-oriented. The basic context entities comprise an observation \( o \) in Equation 1, observation sequence \( os \) in Equation 2, and the evidential statement in Equation 3. These terms are inherited from [22, 23] and represent the context of evaluation in Forensic Lucid. An observation of a property \( P \) has a duration between \( [\text{min}, \text{min} + \text{max}] \) (where \( \text{min} \) is the minimum duration of the observation, \( \text{max} \) is a potential variation from that minimum). This was the original definition of \( o \) [22, 23] and the author later added \( w \) to amend each observation with weight factor or probability or credibility to later further model in accordance with the mathematical theory of evidence [25]. \( t \) is an optional timestamp as in a forensic log for that property. An observation sequence represents, which is a chronologically ordered collection of observations represent a story witnessed by someone or something or encodes a description of some evidence. All these stories (observation sequences, or forensics logs, if you will) all together represent an evidential statement about an incident. The evidential statement is an unordered collection of observation sequences. The property \( P \) itself can encode anything of interest – an element of any data type or even another Forensic Lucid expression, or an object instance hierarchy or an event. It can be arbitrary “deep” in what it can contain as a set of observer computations, state transitions, complex objects, outcomes, measurements, etc.

\[
o = (P, t, \text{min}, \text{max}, w)
\]  

\[
os = \{o_1, \ldots, o_n\}
\]  

\[
es = \{os_1, \ldots, os_m\}
\]

Having constructed the context, one needs to built a transition function \( \Psi \) and its inverse \( \Psi^{-1} \). The generic versions of them are provided by Forensic Lucid [12] based on [23, 22], but the investigation-specific one has to be built, potentially visually (e.g., using a data-flow graph programming tool that can translate into Lucid and back [26]), by the engineering team, which can be done even before the vehicle starts, if the self-forensics aspect is included into the design from the start. The specific \( \Psi^{-1} \) takes evidential statement as an argument and the generic \( \Psi^{-1} \) takes the specific \( \Psi^{-1} \) as an argument as in functional programming.

When the run-time system, such as the General Intensional Programming System (GIPSY) [27, 28, 29, 30], evaluates a Forensic Lucid specification, navigating the evidential statement context of evaluation using intensional operators [12], it traces the execution of the \( \Psi^{-1} \) and computes the possible backtraces of the events from the final observed state of the incident back to the known initial state of the vehicle. The forensic evidence collected as a context for \( \Psi^{-1} \) is compared against a potential hypothesis statement, or a witness (can be device or a sensor or an eyewitness) account to see if they agree, and if they do, what are the possible explanations in the backtraces. The backtraces, if exist, are ordered from the most credible to the least credible (after computing the aggregated credibility score). The investigator is then presented with backtraces of the processed evidence (that can be a large bulk to sift through manually) representing the reconstructed events. If there are no such backtraces, then the witness claim or say manufacturer specification of a faulty component, do not agree with the evidence, which may reasonably provably mean that component is is the cause of the incident or that eyewitness is lying or the component specification is not what it claims to be. It is also possible that we do not have enough
evidence in our knowledge base that we acquired from the incident – in this case the investigator would normally know where to look for more evidence or question more witnesses, etc.

3 Self-Forensics Requirements for Vehicle Design and Incident Investigation

In this section we elaborate in detail on the application of self-forensics and its requirements that must be made formal, if the property to be used in the industry.

Existing self-diagnostics, computer BIOS reports, and S.M.A.R.T. reporting for hard disk as well as many other devices could be a good source for such forensic data computing, i.e. be more forensics-friendly and provide forensics interfaces for self-forensics analysis and investigation as well as allowing engineering teams extracting, analyzing, and reconstructing events using such data. The process has to be supported by the related languages, and tools available to the investigator to model the case, import the actual forensics data gathered, and validate claims and hypotheses of what happened against, potentially large and vast volumes of data, potentially automatically preprocessed with a backtrace of the event reconstruction.

This would be even a greater enhancement and help with the blackboxes, like in planes in the airline industry, or reasoning about events, possibly speeding up the analysis of the anomalies in subsystems.

Most, if not all new cars and other automotive road vehicles these days all have on-board computers and often GPS devices. This by default reduces the cost of adding of the self-forensics units to the design and development of hardware and software components of such vehicles.

3.1 Application

The self-forensics property is meant to embody and formalize all existing and future aspects of self-analysis, self-diagnostics, data collection and storage, and real-time automatic decision making if necessary that were not formalized and categorized as such before and define a well-established category in the industry and academia. In that view, self-forensics encompasses self-diagnostics, blackbox recording, (Self-Monitoring, Analysis, and Reporting Technology) S.M.A.R.T. reporting, and encoding this information in analyzable form of Forensic Lucid contextual logging for in situ or later automated analysis and event reconstruction using the corresponding software tool or tools.

Optional parallel logging of the forensics events during the normal operation of the road vehicles, especially during “extreme” periods of operation, i.e. when it is detected that the speed, internal fluid pressure in any fluid lines, temperature, etc. are over some minimal soft safety threshold, the granularity and frequency of reporting may increase can go off-vehicle via a wireless link to a cell tower or via peer-to-peer ad-hoc mobile wireless network of vehicles to eventually be stored say at the same company that provides the GPS or cellular service to this particular vehicle or its driver. Shipping such forensics logs off-site will have a duplicate copy in case the original gets damaged in the incident. It can also be used by a more powerful computer at the company to do a near real-time analysis of the vehicle’s performance and alert the driver if anything anomalous is detected and predicted to be potentially harmful.

To achieve that all electric, electronic, and mechanical subsystems of a vehicle can have functional units to observe them other for anomalies and log them appropriately for forensics purposes.
3.2 Training

Such forensic specification is also useful to train new engineers on a safety design and testing team, and others involved, in data analysis, to avoid potentially overlooking data and making incorrect ad-hoc decisions.

There are well known log search engines or real-time vulnerability scanners and detectors that, if adapted to our case, would allow the investigator searching and even analyzing the multiple logs or even real-time situation, and even co-relate some events, based on the timestamps, e.g. such as Splunk [33] and Nessus [34], adapted for the use in a vehicle’s on-board computer, yet if applied to our case they would still be tedious and time consuming to work with by an investigator when examining the logs and detected evidence, that could be very numerous.

In an Forensic Lucid-based expert system (that’s what was the original purpose of Forensic Lucid in the first place in cybercrime investigations) one can accumulate a number of contextual facts from the self-forensic evidence and the trainees can construct their theories of what happened and see of their theories agree with the evidential data. Over time, (unlike in most cybercrime investigates) it can accumulate the general enough contextual knowledge base of encoded facts that can be analyzed globally and on the web. The data can be shared across manufactures and mechanical and software engineers involved.

3.3 Requirements

Here we briefly define the requirements scope for the self-forensics property adapted to road vehicle design:

• Should be optional if constrained by the budget, but should be strongly recommended to be included. Must not be optional for mission critical and safety-critical road vehicles (e.g. military, police, ambulance, fire trucks, etc.).

• Must be included in the design at all times.

• Must cover all the self-diagnostics events mentioned earlier as well as any design-specific events and monitoring.

• Must have a formal specification (that what it makes it different from just self-diagnostics).

• Must have tools for automated reasoning and reporting about incident analysis matching the specification.

• Context should be synthesized in the terms of system specification involving the incidents, e.g. parts and the software and hardware engineering design specification should be formally encoded (e.g. in Forensic Lucid).

• Preservation of forensic evidence must be atomic, reliable, robust, and durable.

• The forensic data must be able to include any or all related non-forensic data for analysis when needed, including measurements taken around the time of incident or even the entire trace of a lifetime of a system component logged somewhere for automated analysis and event reconstruction.

• Levels of forensic logging and detail should be optionally configurable in collaboration with other design requirements in order not to hog other activities, create significant overhead, or fill in the bandwidth of the wireless connection or log storage.
3.4 Limitations

The self-forensics autonomic property is very beneficial to have for automated analysis of incidents in road vehicles and the like, but it probably cannot be mandated as absolutely required due to a number of limitations it creates. However, whenever the monetary and time budgets allow, it should be included in the design and development of the road vehicle parts or software systems capable of self-monitoring and reporting of encoded forensic data.

Here are some most prominent limitations:

- The cost of the vehicle will obviously increase from manufacturing, to maintenance, and the end-user buying price.
- If built into software, the design and development requires functional long-term storage and CPU power.
- Likely increase of bandwidth requirements; if the more than twice bandwidth and storage used.
- An overhead overall if collect forensics data continuously. Can be offloaded along with the control data.
- Ideally should be in ROM or similar flash type of memory; but should allow firmware and software upgrades.
- Current computer logging within vehicles are not designed to be for the work presented here – Forensic Lucid-based self-forensics analysis, so there will have to be an effort to adapt it if Forensic Lucid specifications become an industry standard. Fortunately, traditional existing logging can be converted to use the Forensic Lucid expressions without much difficulty, that would greatly simplify forensic analysis of such data.
- We do not tackle other autonomic requirements of the system assuming their complete coverage and presence in the system from the earlier developments and literature, such as self-healing, self-protection, etc.
- Transition function $\psi$ and its inverse $\Psi^{-1}$ has to be modeled by the engineering team throughout the design phase and encoded in Forensic Lucid. Luckily the DFG IDE [26], like a CAD application is to be available.
- Manufacturers or some external certifying agency has to be involved to make sure the self-forensic components function as intended to prevent the manufacturer to circumvent self-incriminating evidence thereby promoting the quality and accountability of vehicle manufactures.

3.5 Advantages

Having Forensic Lucid helps scripting the forensics events in a log in the road vehicle’s computer or a blackbox. The blackbox can contain the forensic data encoded anyhow including forensics expressions, XML, or just compressed binary and using external tool to convert it to a Forensic Lucid specification for further evaluation by investigators. Forensic Lucid is context-aware, built upon the intensional logic [35, 36] and dialect that existed in the literature and math for more then 30 years.
3.6 Small Example

- Self-forensic hardware sensors observe systems (electrical and mechanic) of a road vehicle.
- Every engineering event is forensically logged.
- Each forensic sensor may observes several systems or subsystems.
- Each sensor composes a “story” of an observational sequence a particular system or a component in as a Forensic Lucid context and the component specification is known at the manufacture time and encoded as a Forensic Lucid specification in advance.
- A collection of sensor witness stories from multiple sensors, properly encoded, represent the evidential statement.
- An incident happens; engineers define theories about what happened. The theories are encoded as observation sequences. When evaluated against the evidential statements from all sensors the events are co-related and reconstructed according to the Forensic Lucid semantics.

Then the evaluating system (e.g. GIPSY) can automatically verify the theory automatically against the context of evidential statement and if the theory $T$ agrees with the evidence, meaning this theory has an explanation within the given evidence (and the amount of evidence can be significantly large for “eyeballing” it by humans), then likely the theory is a possible explanation of what has happened. It is possible to have multiple explanations and multiple theories agreeing with the evidence. In the latter case usually the “longer” (in the amount of events and observations involved) theory is preferred or the one that has a higher cumulative weight/credibility $w$.

4 Conclusion and Future Work

We would like to conclude with the remarks that we stated at the beginning – that the self-forensics modules and components, both hardware sensors, a simpler analogue of a blackbox, and software components should be included into the modern road vehicle design for real-time and post-mortem forensic log data analysis in the Forensic Lucid-encoded form to aid investigation and event reconstruction with the formal approach to make the investigation complete not only from the outside, but also from the inside by using the forensics data. Furthermore, such data can be used during the crash testing of the road vehicles by the manufacturer as well as to train the engineering teams and the investigators to do a more complete analysis with an aid of the Forensic Lucid-based expert system.

We also discuss the potential limitations of the approach. In our future work we will attempt to address the limitations as well as complete some other intermediate items along the way, specifically.

Future Work.

- Estimate the feasibility of “back-porting” the self-forensics modules and components into the existing fleets of road vehicles as well as the costs of storage and maintenance of such data, when it expires, and who has a control over it.
- Amend the Autonomic System Specification Language (ASSL) \cite{37, 38, 39, 40} to handle the self-forensic property along with its formal specification and verification.
- Implement the notion of self-forensics in the GIPSY \cite{27, 28, 29, 30, 41} and DMARF \cite{42, 43, 44, 45} systems the author is closely working on.
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- Finalize implementation of the Forensic Lucid compiler and the development and run-time environment.

- Implement large realistic cases encoded in Forensic Lucid to test and validate various aspects of correctness, performance, and usability.

- Industrialize and standardize the concept in the industry.

- Resolve and map out privacy issues with external reporting of the forensic evidence via the wireless transmission and the applicable laws.

- Durability.

- Cost analysis of the self-forensic system deployment in a road vehicle.

- This research can aid crash investigations not only in automotive vehicles, but technically in all vehicle types, e.g. in the aviation industry by incorporating the self-forensics features and components into helicopters, planes, etc. to aid crash investigations such as [46, 47].

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