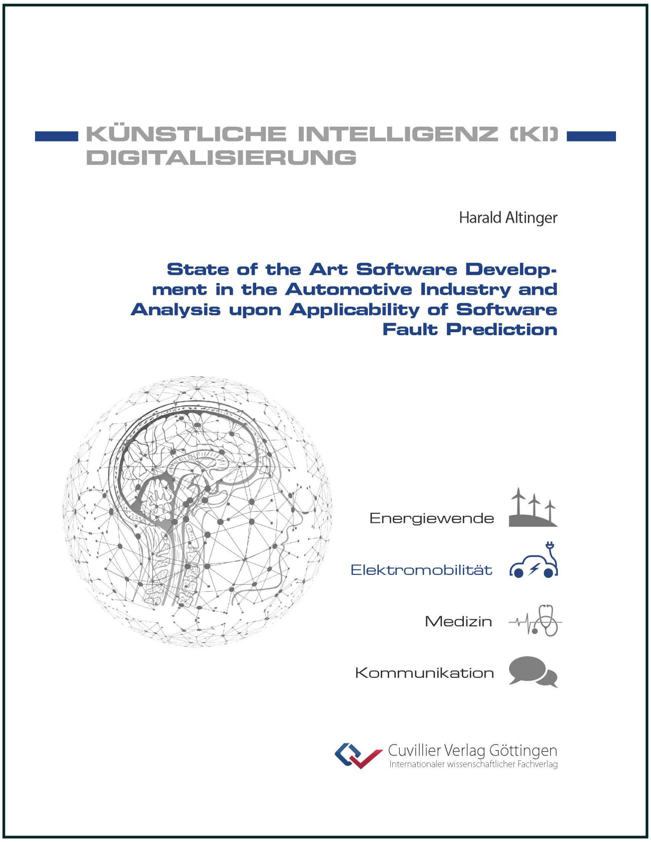
Harald Altinger (Autor)

State of the Art Software Development in the Automotive Industry and Analysis upon Applicability of Software Fault Prediction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Harald Altinger

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1. Introduction

This chapter will start with a general motivation 1.1 to automotive software engineering as a computer science research field, continuous with the identified problems 1.2 and research questions on software testing within the automotive industry, presents an overview to the thesis contribution 1.3 and concludes with the thesis organization 1.4.

1.1. Motivation

Within the last decade **Software gained importance in cars**. A modern day premium car, *example given* the 2015 Audi A4 [1] may be equipped with up to 90 Electronic Control Unit (ECU), two high resolution displays, two Subscriber Identification Module (SIM) cards, 11 communication networks (Controller Area Network (CAN), FlexRay, Media Oriented Systems Transport (MOST)) and up to six antenna systems (radio, Keyless Entry Start and Exit System (Kessy), WiFi, *etc.*) ensuring wireless communication between the car and various infrastructure. From a computer scientist's perspective a modern day car is a heterogeneous network of embedded computers performing local and distributed tasks. In addition to transport capabilities customers demand up to date entertainment (including music, video or online streaming) and comfort(climate control, massage seats, *etc.*) in a modern day car. Various features, *example given* Advanced Driver Assistance Systems (ADAS), rely on data fusion between multiple sensors and pre calculated values on various ECU. A wide range of sensors starting from simple switches or rotary encoders to advanced Global Positioning System (GPS) Antennas or Radar Sensors will be used to sense the car's environment or interact with the driver. Realizing innovative ADAS like Adaptive Cruise Control (ACC) or Matrix headlamps requires fusioning pre processed measurement data from a camera sensor and a radar sensor as well as a lookup from the road traffic database. This requires four ECU to

(a) Audi A8 Electric wires diagram. Picture extracted from [3]

(b) Audi A4 Electric wires diagram. Picture extracted from [1]

Figure 1.1.: Audi A4 and A8 schematic showing the electric wiring harness

work together in realizing one specific driving function. Figure 1.1 shows two modern day premium cars with all their electronic systems and wires, which sum up to 2.5 km in total length, leaving a modern day car to be one of the most technical places within a humans daily live. Following Pretschner *et al.* [2] a 2007 BMW 7 Series contained about 270 software based functions and 67 ECU powered by 65 megabyte of data, the 2010 Model has been expected to contain one gigabyte of software.

The amount of software required to operate a car or an aircraft has increased during past years, even putting the automotive domain in the lead. Robert Charette [4] compares the complexity between an aircraft and a car demonstrating that it requires more Lines Of Code (LOC) to operate a typical car than an aircraft. Dvorak *et al.* [5] states that software realized functionality within a military aircraft raises from below 10% on an 1960is F-4 to 80% on a modern day F-22. Similarly the author states a representative car from General Motors (GM) rises from 100.000 LOC within the 1970is up to 1.000.000 LOC in 2010. Broy [6] states modern day premium cars can contain up to 100.000.000 LOC. In previous works Broy [7] reveals **electronics and software development consumes up to 40% of the whole development budget** nowadays. This is in line with a forecast by Siemens released in 2005, see Aschenbrenner [8]. Similarly a market research from Ehmer [9] states that 20% of the car's total development budget in 2000 will increase to 35% by 2010. They will be distributed among 2% basic software, 8% operating system and 28% application software.

A car recall costs money. Whenever a malfunction within a car is a threat to human life, the law forces an Original Equipment Manufacturer (OEM) to perform repairs. In terms of software this means developing a hotfix and distributing it. Most OEM do not equip their cars with over the air update capabilities this means the car has to be moved into a workshop. Within recent years there have been multiple recalls, compare Figure 1.2. The total number can be extracted by querying the National Highway Traffic Safety Administration (NHTSA) database [10], the amount of software related recalls can been extracted counting each entry containing the terms "software" or "program" within the recall description or required repair action. The number of sold vehicles can be gathered from Wards Auto [11]. The majority of recalls were due to mechanical deficits, but the share of software related recalls is increasing. Within the automotive industry such a recall can cost millions, as an OEM has to pay for contacting the customer, maybe a rental car and the workshop to replace the software. In addition, National Automobile Dealers Association (NADA) published a Whitepaper [12] analysing the impact of recalls on a cars (retail)value. They recognized an increasing number of affected vehicles by recalls within the last decade. Analysing an OEM's average car price compared to competitors they found clear impacts of a recall on achievable market prices, *example given* Toyota dropped by -20% after the 2009 recall on self accelerating models. The authors conclude avoiding a recall will be of economic interest.

Finding bugs later costs more money. A recent Whitepaper from Klocwork [14] stated that finding bugs in early development phases might cost 25$, in a later phase this could climb up to 16.000$. The authors values are based on standard software. Tassey [15] presents multiple analysis concerning the costs when finding bugs in different development stages. The author states 70% of all errors are introduced during the requirements phase but 50% of all bugs will be discovered during the integration testing phase. Further the authors analysed the cost of fixing bugs, see Figure 1.3. In line

[1]Model-year is the first year where a car type is introduced. If a recall is reported in 2008 and 2010, but the car was lunched in 2004, the recall will always bee counted for Model-year 2004. One car can be affected by multiple recalls during its lifetime. The recall data is available via NHTSA [10], the sale statistic via Wards [11].

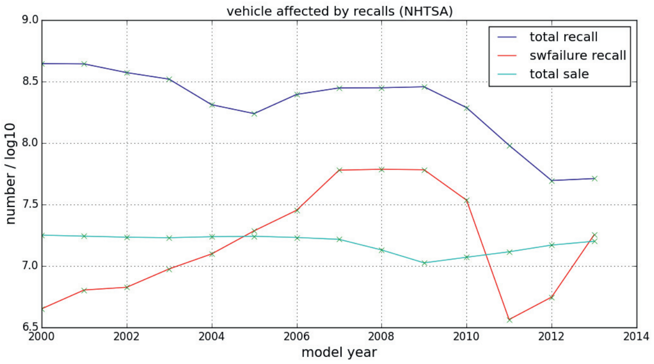

Figure 1.2.: NHTSA recall statistics on Model-year 2000 - 2014, comparing recalls in total with software caused recalls and sales [1]. One can see more recalls than sold vehicles within multiple years. The graphic has been extracted from Altinger *et al.* [13].

with Capers [16] the later a defect is detected, the more expensive it is to fix it. In terms of the automotive industry the numbers will be even higher, as the law forces antecedent tests to be repeated. The majority of tests requires expensive hardware and personnel *example given* to ride prototype cars for a defined mileage.

Within a software's Product Life Cycle (PLC), maintenance can cause the highest costs. ISO/IEC 14764 [17] defines software maintenance as the modification of a product after delivery to a customer. The aim of such a modification is to correct faults, to improve performance or to adopt other quality attributes of the product. As analysed by Kozlov *et al.* [18] 49% to 75% of the total software costs are caused by maintenance. Kozlov *et al.* examined data between the 1970s and 1990s. Recent data published by Confora *et al.* [19] indicate even more than 80% of the total PLC costs are caused by maintenance nowadays. Shull *et al.* [20] states that fixing a software fault during maintenance caused higher costs than finding and fixing it during the early phase of the software's PLC, which is in line with Capers [16]. Even if concrete figures vary, Shull *et al.* [20] analysed that

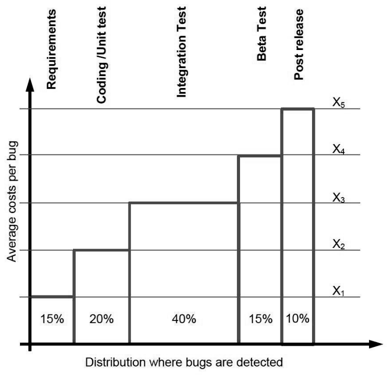

Figure 1.3.: Costs to fix detected bugs, the graphic has been adopted from Tassey [15].

the effort increase by 100:1 for critical defects on large projects and 2:1 for non-severe bugs discovered after release.

Summarizing this chapter's arguments, the share of software increases, fixing bugs out in the field (after release) costs huge amount of money and has a negative impact on the OEM's reputation. Thus finding bugs during early development stages is of economic interest.

1.2. Problem Statement

As stated in the previous chapter, developing software is a complex and expensive task. According to Broy [6] and Aschenbrenner [8] 30-50% from a car's total development costs will be dedicated to software by 2030. Testing has always been a core part of Automotive engineering, as the W-Development process defines a testing stage for every development stage, compare Jin-Hua *et al.* [21]. Indicators where to particular spend TestCase (TC) are welcome to increase efficiency in testing.

The following research questions are identified:

RQ1: What are the common tools automotive software engineers use to specify requirements and write their software?

RQ2: Is it possible to use fault prediction within automotive software projects?

- **RQ 2.1:** Does fault prediction benefit from restrictive development guidelines (Coding-standards and development processes)?
- **RQ 2.2:** What are influential parameters for fault prediction to performing usefully?
- **RQ 2.3:** Do (re)sampling strategies influence the achievable performance?
- **RQ 2.4:** Is it possible to establish Cross-Project Fault Prediction (CPFP) within the restrictive development settings?

RQ3: Which metrics perform best for generated code within automotive software?

- **RQ 3.1:** Which metrics are independent and share no correlation with others?
- **RQ 3.2:** Do metrics represent the occurred bugs?

RQ4: What are good fault predicting methods and what performance can be achieved?

1.3. Thesis Statement

Main parts of this thesis were published on international Workshops and Conferences and are peer reviewed:

- Altinger *et al.* [13] commits to answer **RQ1** by performing a representative survey upon tools and methods.
- Altinger *et al.* [22][2]presents further insights into software methods and development procedures within the automotive industry. This work contributes to answer **RQ1**.
- Altinger *et al.* [23] releases an industry grade dataset containing software metrics on automotive software projects aiming to answer **RQ3** and **RQ3.1** by presenting correlation analysis upon those measurements.
- Altinger *et al.* [24] presents work on Software Fault Prediction (SFP) and CPFP answering **RQ2** by using machine learning classifiers to predict failures. Comparing the achieved performance values with literature **RQ2.1** will be answered. Correlation analysis and information ranking will be used to address **RQ2.2**. Main work will be on **RQ2.4** using state of the art literature methods and comparing their performance. Finally **RQ4** will be answered using a Principle Component Analysis (PCA) on the metric data.
- Altinger *et al.* [25] reports on influences of resampling algorithm to bug prediction performance. This work commits to answer **RQ2.3**.
- Altinger *et al.* [26] presents work on bug analysis to response on **RQ3.2**.

A detailed annotated publication list is given in Section A.1.

[2]This publication is submitted to review and is not published at date of release of this thesis

1.4. Thesis Organization

The thesis will be organized as follows. Starting with Chapter 2 to present the automotive industry as the research area and Chapter 3 containing the related literature with a focus on the field of fault prediction. Chapter 4 reviews a conducted questionnaire survey on tools used to specify, develop and test automotive software. An analysis upon three real world software projects is presented in Chapter 5. The obtained results on fault prediction are contained within Chapter 6. Finally Chapter 7 gives concluding remarks and a preview to further research topics.

2. Field of Study - Automotive Software Development

This chapter gives a short introduction to the automotive industry 2.1 and clarifies some domain specific environment parameters 2.2 along with common testing approaches 2.3. This examination will focus mainly on a computer science perspective.
For a more wider introduction to automotive engineering, including other disciplines such as computer science, the reader is redirected to Winner *et al.* [27], Braess *et al.* [28] and Crolla [29].

2.1. Automotive domain

Compared to the consumer electronic industry the automotive domain has a **rather long PLC**. Volpato and Stoccchetti [30] analysed cars PLC data between 1970 and 2006. They report on small cars to be redeemed by the new model after five years, premium cars after eight years, with a strong trend to shorter cycles. This is in line with Broy *et al.* [31] where they state a PLC is roughly seven to eight years, service and spare parts may last up to 15 years. According to the Kraftfahr Bundesamt (English: German Federal Motor Transport Authority) (KBA) [32] statistically cars in Germany are decommissioned after 8,8 years in use. Considering the average three to four year development phase as reported by Crolla [29], see Figure 2.6, some components development might be 18 to 20 years ago when a car is still on the road. Sabadka [33] predicts a reduction of a cars development time from 40 months to 25 in 2013 and further to 20 months in 2018. Using the VolksWagen (VW) Golf as a case story he analysis a PLC reduction from ten years in the late 1970is to three years in late 2000. In contrast, typical consumer products are replaced every two to three years according to Andrae and Andersen [34], software might be updated within much shorter cycles.

Most software runs on ECU with strict hard real-time constraints, memory and computing power is always limited. A modern day car can be seen as a heterogeneous network of up to 90ECU performing local and distributed computing tasks. Some nodes acquire data via a sensor interface, some pre-process data and some aggregate data, others control actuators. The automotive environment is rather harsh, *example given* the operational temperature is specified between -40° and +120°, shock, Electrostatic Discharge (ESD), vibration, *etc.* Tils [35] presented a rather good overview to all physical requirements to car electronics. These limitations may cause the Central Processing Unit (CPU) to run in throttled computation mode to fulfil operation requirements.

Hartung *et al.* [36] addresses the **variation diversity** within automobiles and visualizes them with examples. Pretschner *et al.* [2] uses 80 components which a customer can order, availability may depend on the country, to calculate 2^{80} variants an OEM can assemble electronics. During production the car is equipped with the ECU, but the actual software configuration is generated and deployed in the production line depending on the configuration the customer ordered. This causes a high number of conditions within the software, to cover all options. Peleska *et al.* [37] released an original software model visualizing the high amount of states and conditions to realize a simple car's turn indicator.

The Ultimate time goal: Start Of Production (SOP), the first day when a new model is built. This day requires all developments to be completed, all software to be tested and all certificates and accreditation documents to be issued. Long planning cycles are invested to solve logistic topics, all components need to pass qualification audits. Crolla [29] gives a brief overview to these milestones, see Figure 2.6. Once the SOP day is defined, customers may no longer order the old model, and logistic does not stock up components from the old model. This means, that from a certain point in time, it is not possible to extend the production of the old model anymore. Assuming a cycle time during assembly of about 70 - 90seconds and an average product price in the five digits regions, a production stop for a day can easily sum up to millions of EUR.