Systematic Evaluation of Sandboxed Software Deployment for Real-time Software on the Example of a Self-Driving Heavy Vehicle

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Abstract—Companies developing and maintaining software-only products like web shops aim for establishing persistent links to their software running in the field. Monitoring data from real usage scenarios allows for a number of improvements in the software life-cycle, such as quick identification and solution of issues, and elicitation of requirements from previously unexpected usage. While the processes of continuous integration, continuous deployment, and continuous experimentation using sandboxing technologies are becoming well established in said software-only products, adopting similar practices for the automotive domain is more complex mainly due to real-time and safety constraints. In this paper, we systematically evaluate sandboxed software deployment in the context of a self-driving heavy vehicle that participated in the 2016 Grand Cooperative Driving Challenge (GCDC) in The Netherlands. We measured the system’s scheduling precision after deploying applications in four different execution environments. Our results indicate that there is no significant difference in performance and overhead when sandboxed environments are used compared to natively deployed software. Thus, recent trends in software architecting, packaging, and maintenance using microservices encapsulated in sandboxes will help to realize similar software and system engineering for cyber-physical systems.

I. INTRODUCTION

Companies that produce and maintain software-only products, i.e., products that are only constituted with software and are pre-dominantly executed in cloud-environments like web shops or cloud-based applications, have started to strive for achieving shorter product deployment cycles. Their goal is to tighten software integration and software deployment up to their customers. When these processes are reliably established, companies are able to closely monitor their products in real usage scenarios from their customers and can collect highly relevant data thereabouts. This data is of essential business interest to better understand the products in the field, maintain them in case of issues, and to gradually introduce new features and observe their adoption.

For example, companies like Facebook and Netflix have established mechanisms to enable continuous deployment that would allow software updates as often as hundreds of times a day [1]. These companies ultimately aim for a software engineering process that integrates near real-time product feedback data as crucial method for continuous business and product innovation.

A key-enabling technology for such software-only products is resource isolation that is strictly separating system resources like CPU time, network devices, or inter-process communication resources; today’s leading environments are the tool suite Docker [2], [3] or Google’s Iacrylic (from let me contain that for you) [4] that encapsulates cloud-based applications. The key concept is to package all relevant software product dependencies in self-contained bundles that can be easily deployed, traced, archived, and even safely rolled back in case of issues.

This study is an extension of a master thesis presented in [5], where further details are presented and available.

A. Problem Domain & Motivation

Continuously developing, integrating, and deploying is challenging with software-only systems, i.e., systems that are not dependent on their surrounding physical environments. However, these tasks become even more challenging in the domain of self-driving vehicles, where applications are safety-critical and most of the times, even the underlying hardware is limited in capacity. In addition, this type of cyber-physical system (CPS) heavily relies on real-time...
capabilities, making the scheduling precision a fundamental aspect to consider throughout the entire lifecycle. This study is mainly motivated by our experience with a self-driving truck depicted in Fig. 1 that participated in the 2016 Grand Cooperative Driving Challenge (GCDC)\footnote{http://www.gcdc.net}. The competition includes a number of collaborative maneuvers that must be safely performed by participating vehicles. As there are several team members constantly working on the truck’s software, it has become evident that the project would greatly benefit from a reliable, traceable, and structured deployment process. On the other hand, significant performance overhead in the software execution must be avoided apparently.

B. Research Goal & Research Questions

The goal of this work is to systematically evaluate the influence of sandboxed execution environments for applications from the automotive domain. We are particularly interested in studying the impact on two quality attributes of the system: Scheduling precision and input/output performance. Hence, in this article the following research questions are addressed:

RQ-1: How does the execution environment influence the scheduling precision of a given application?

RQ-2: How does the execution environment influence the input/output performance of a given application?

C. Contributions of the Article

We demonstrate the impact of using container-based technology in relation to the underlying operating system (i.e., real-time kernel) on the performance of a given automotive application. To achieve this, we conduct a multi-method research approach that includes (i) an investigation of the current state-of-the-art in the area; (ii) a controlled experiment on desk using example applications; and (iii) a validation of the results in a real-world scenario using the aforementioned Volvo FH truck. To the best of our knowledge, this work is the first of its kind to evaluate the use of Docker in the autonomous vehicles business.

D. Structure of the Article

The remainder of this article is structured as follows. Sec. II contains the methodology used in this work. In Sec. III, the related work is presented in the form of a literature review. Sec. IV contains a description of the experiments in a controlled environment and in the truck. In Sec. V we present the results, followed by an analysis and discussion in Sec. VI. Finally, conclusion and future work are described in Sec. VII.

II. METHODOLOGY

In order to achieve an understanding of how the execution environment influences the performance of applications, three studies are designed in a way that they complemented each other. First, we perform a literature review using key terms in the search, followed by the inclusion of additional papers using the snowballing approach [6]. Then, we conduct a controlled experiment on desk to measure the scheduling precision and I/O performance of sample applications when deployed on four different environments. Finally, we conduct an experiment using a real-world application that is currently deployed on the self-driving truck. The latter experiment is designed in a way that the findings from the first study can be validated.

The goal with such design is to obtain meaningful results from different sources, combine them, and contribute towards a safe, robust, and reliable software deployment process in the domain of self-driving vehicles. Performing such multi-method research allows collection of data of different types, resulting in a wider coverage of the problem space [7].

III. LITERATURE REVIEW

Performing a literature review in a way that it is systematic brings a number of benefits. The steps are replicable, justified, and the results of the study provide basis for future research in a given area. In the present work, we perform a light-weight literature review based on the snowballing approach [6]. The technique consists of searching for related work by investigating citations from a known set of relevant papers. In summary, the steps to conduct a snowballing procedure include (i) selecting a set of papers referred to as the start set; (ii) apply forward snowballing (citation analysis) in the start set; and (iii) apply backward snowballing on each paper identified. This process iterates until no new relevant papers are found.

Our start set consists of papers found through a search in the Scopus digital library [8]. The search string is presented in Table I. It contains key terms concerning performance evaluation of virtualization/container approaches. We also include the term Docker as authors may have different definitions for the framework, yet we are interested in capturing papers discussing it. The search resulted in 215 papers that had their titles and abstracts critically evaluated according to our inclusion and exclusion criteria. Inclusion criteria include papers presenting benchmarking activities and experiences with Docker. Exclusion criteria exclude, for example, papers in languages other than English and short papers pointing to online material.

The forward and backward snowballing procedures resulted in 10 highly relevant papers which were selected as primary studies. In addition to this set, we included 2 external papers that were not found during the search, even though they are relevant to the context of this study. The final set was critically appraised in the search for insights that would aid in the understanding of the state-of-the-art of software virtualization/containers. The next subsection contains selected outcomes from the search.

| TABLE I SEARCH STRING IN SCOPUS |
|----------------------------------|
| TITLE-ABS-KEY(Performance OR Evaluation OR Container-Based OR Linux Containers OR Lightweight Virtualization OR Container Cloud OR Docker) AND (LIMIT-TO(SUBJAREA,”COMP”) |
A. Outcomes of the Review

The challenge and need for maintaining, deploying, and configuring software for embedded, cyber-physical systems is identified in current literature [9], [10]. Berger [9] investigates a continuous deployment (CD) process for self-driving miniature vehicles using Docker containers. Multiple containers are used to create binary packages from source that are signed and tested for different hardware architectures, exemplifying a possible CD process for CPSs. The trade-off of virtualization is widely discussed in literature. Krylovskiy [10] evaluates Docker for resource-constrained devices, identifying negligible overhead and even outperforming native execution in some tests. Similar performance characteristics are identified by Felter et al. [11], identifying negligible overhead for CPU and memory performance. Felter et al. recommend that for input/output-intensive workloads, virtualization should be used carefully. As Felter et al. use the AUFS storage driver for their evaluation, we use the Overlay storage driver as it is considered to be the default option for Docker in the future.

Negligible performance overhead is also identified by Raho et al. [12] who identify a 3.2% CPU performance decay when using Docker on an ARM device. In respect to self-driving vehicles, however, there lacks research using Docker for real-time applications. Mao et al. [13] investigate using Docker for time-sensitive telecommunications networks in the cloud. A benchmarking tool is used to report the computational worst case execution time when executed natively and within a container using three different operating system kernels. The results show that the difference between Docker and native execution is only 2 µs when using the preempt_rt real-time Linux kernel irrespective to system load. Latency when using the real-time kernel is improved by 13.9 times for Docker (from 446 µs to 32 µs) and 7.8 times for native execution (from 234 µs to 30 µs) in comparison to a vanilla kernel [13]. The authors concluded that in order to satisfy real-time demands, a finely-tuned real-time Linux kernel must be used to achieve near native performance.

Furthermore, the authors identified considerable overhead when using Docker on multiple hosts. This finding is also confirmed by Ruiz et al. [14] who identify a high cost when using multiple containers on different nodes. The authors of [15] also investigate using Docker to realize a modular CPS architecture design. The authors encapsulate computational nodes into containers to improve security and to ease system administration through modularity and scalability, decoupling the complexity of a CPS into smaller subsystems. They point out the benefit that teams can work independently and concurrently on Docker images as well as the need of using a real-time enabled Linux kernel. Current literature points to the fact that Docker can be used for CPS due to negligible overhead identified in current research. However, further evidence is needed for the area of automated driving.

IV. Experiments

The aim of the controlled experiment is to systematically evaluate the scheduling precision and input/output performance of two sample applications; both during native execution and encapsulated into a sandboxed environment (Docker). Scheduling precision refers to how precisely, in measures of time, the CPU scheduler is able to execute an operation from when the operation was first called. Whereas the input/output performance refers to measuring the performance of camera input and disk output, namely the time it takes capturing an image and saving it on the disk. Through a sequence of controlled steps, the sample applications are executed in four different execution environments. The execution environments consist of an alternation of (i) executing the sample applications natively or sandboxed within a Docker container and (ii) executing the sample applications on a target system with a vanilla or a real-time enabled kernel. Understanding how the respective execution environments influence the scheduling precision and input/output performance will ultimately decide how deterministic, with respect to time, the system is to uncover the performance cost of using Docker for software deployment.

The two sample applications, named Pi and Pi/IO component, are realized with the open-source development framework OpenDaVINCI\(^2\). Measurement points in the form of timestamps are captured during runtime of the sample applications to uncover the timing behavior of the respective application. The Pi component, used to measure scheduling precision, is tasked to calculate the next digit of Pi until it reaches 80% of its designated time slice. The remaining 20% should be spent sleeping the process. For the experiments, the 80% CPU load was established based on our observations when executing real-life scenarios with the truck. Four measurement points are captured during runtime: the timing of OpenDaVINCI’s middleware (named Overhead 1 and Overhead 2), the time duration for calculating Pi (Pi Calculation) and the amount of time the process sleeps (Sleep). The Pi/IO component, used to measure input/output performance, is tasked to capture an image (Camera Input) and store it to disk (Disk Output).

Treatments used for assessing the impact of factors that are specific to the execution environment (e.g. execution context and deployment context). During execution of the sample applications, system load is applied to the target system in order to traverse kernel code paths and to mimic runtime load of a self-driving vehicle. Load is applied to the system via a user-space application (stress-ng\(^3\)), spawning two worker threads that apply CPU load at 80% with scheduling priority 48. The controlled experiment is executed on an AEC 6950 embedded personal computer\(^4\). The Linux kernel version 3.18.25 is chosen for both vanilla and real-time enabled kernel. A USB webcam Logitech c930e is used for measuring the I/O performance. Ingo Molnar’s real-time patch (preempt_rt) is used to bring real-time capabilities to the kernel. The Docker storage driver Overlay is used in the experiment, instead of the default AUFS driver, which is

\(^2\)http://www.opendavinci.org
\(^3\)http://goo.gl/0SWuFW
\(^4\)http://www.aaeon.com/en/p/fanless-embedded-computers-aec-6950/
known for performance issues.

The results from the controlled experiment give recommendation on which execution environment is best suited to meet real-time requirements. That respective execution environment is applied to the self-driving heavy vehicle (Volvo FH16 truck), where parts of the controlled experiment are executed in order to validate the results. The Pi Component is executed exclusively on the self-driving truck as the camera hardware setup is networked and differ greatly from that of the controlled experiment and would require modifications to the sample application, which excludes the Pi/IO component for the uncontrolled tests.

The intention of the real-life use case is to further understand the impact of using Docker for software deployment on a system with all required operations to enable self-driving capabilities running simultaneously as system load. Consequently, the environment is less-controlled from the researchers’ access, however, it is more realistic in the sense of operational load. The sample application Pi Component is used to capture data, with the exact same execution parameters and data collection procedure on precisely the same target system, where the difference between the experiments is seen in the applied system stress.

V. RESULTS

In this section, the results from the experiments are introduced. Fig. 2 presents the results of running the first experimental unit, namely Pi Component. It is run with a frequency of 100 Hz in four execution environments. Both figures address the scheduling precision of the execution environments. Fig. 2A depicts the average time deadline for each of the four execution environments, while Fig. 2B depicts how deterministic each of the execution environments are, i.e. how much does each executing time-slice vary from the resulted mean time deadline.

Executing the experimental unit on a system with a Linux vanilla kernel results in an average time deadline violation of approximately 10%. Fig. 2B presents the most deterministic execution environment is executing the experimental unit on a system with a preempt\_rt real-time Linux kernel. The standard deviation of the sleep execution on a system with native execution and Linux vanilla kernel is roughly 2400 µs. The total standard deviation of the same execution environment is approximately 7000 µs. Both figures show no noticeable difference between executing the experimental unit in Docker or natively in respect to both the determinism or scheduling precision of a system. Outliers, which are apparent, are included in the results and have not been disregarded.

The two charts in Fig. 3 present the camera and disk performance for each of the execution environments running the second experimental unit, namely Pi/IO Component, at 10 Hz. Fig. 3A shows that both operations of capturing an image and saving it to disk consumes on average of approximately 7% and 12% of the total time-slice. The execution environment with the worst input/output performance is a system running with a preempt\_rt real-time Linux kernel and executing the experimental unit either natively or in a Docker container. Fig. 3B presents the standard deviation of the input and output operations which depicts how deterministic each execution environment is in regards to its input and output performance. Each of the execution environments have approximately the same standard deviation. Fig. 3B shows that the input and output operations on the system with an preempt\_rt real-time Linux kernel results in a higher standard deviation, thus less deterministic in regards to such operations.

A MANOVA test was conducted on all extracted data, including the outliers. This test was conducted to understand the statistical impact each treatment have on the dependent variables, i.e. scheduling precision and input and output performance. The MANOVA resulted in all treatments having
It is not sufficient to look at the impact of the deployment strategy exclusively to fully comprehend what execution environment is suitable to adopt for a system of a self-driving vehicle. Additional factors play crucial parts of the performance within such a system. Further factors such as kernel and system load are crucial to acknowledge when deciding upon the execution environment. This is confirmed by the results, which show that utilizing Docker for the deployment strategy of a self-driving vehicle has negligible impact on the performance of the system. The literature review further plays an integral role in the findings, as it has been pointed out in related work that a Docker solution does not add substantial overhead to a given system’s performance.

The data gathered from all executions in both experiments have shown that Docker is not the crucial factor to focus on when deciding which execution environment to adopt for a self-driving vehicle. Both the controlled and uncontrolled experiments presented similar results in regards to the scheduling precision, whereas the controlled experiment extended the scope for the input/output performance of the system. The data extracted from each environment has shown that selecting the correct kernel has a greater importance on the scheduling precision and input/output performance of a self-driving vehicle, where both effect size and the presented graphs convey convincing evidence.

This is in line with previous research exploring the impact of Docker utilizing a preempt\_rt real-time Linux kernel (cf. Mao et al. [13]). They present that the difference between a native execution and executing within a Docker container is a mere 2\µs. While the latency is improved by 13.9 times when utilizing a preempt\_rt real-time Linux kernel in comparison to a generic Linux kernel. Further research has also shown similar results when utilizing Docker for the deployment strategy where Felter et al. [11] found that Docker has negligible overhead in regards to CPU and memory performance, and Krylovskiy [10] presents negligible overhead introduced by Docker when executed with an ARM CPU.

Other performance aspects such as input/output performance are taken into consideration during the controlled experiment. The results show that executing the application within a Docker container has negligible impact on the input/output performance, while utilizing a preempt\_rt real-time Linux kernel had a negative impact on the input/output performance of the application. This may be explained by the system’s preemptive approach where the input/output operations can be preempted by other processes and thus, increasing the time required to execute the operations.

The results regarding the determinism of the execution environment captured in the uncontrolled experiment on the self-driving truck differ from those captured in the controlled experiment. Where the uncontrolled experiment shows that Docker has an impact on how deterministic a system is when executed alongside components, which enable the self-driving capabilities of the truck. However, the results suggest that the load introduced in the controlled experiment is no-

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**VI. ANALYSIS & DISCUSSION**

![Fig. 4. Scheduling precision results from the uncontrolled experiment.](image)

A significant P-Value thus indicating a significant impact for all treatments (i.e. alternating deployment and kernel). However, the P-Value can not be fully trusted as this study has a vast amount of sample data which carries a risk of Type I error [16], thus an effect size is extracted to fully comprehend what that significant impact is in reality. Table II presents the results from the MANOVA as well as the effect sizes for each of the experimental units. The first three values depict the results from each of the alternating factors within the execution environment of the experimental unit Pi Component.

As the effect size and Pillai’s Trace are both lower for the deployment treatment, in comparison with the kernel treatment, it suggests that switching between a vanilla Linux kernel and a preempt\_rt real-time Linux kernel has a greater impact on the scheduling precision and input/output performance in comparison to the alternation between executing natively and within a Docker container.

Finally, after executing the controlled experiment, an uncontrolled experiment was carried out on a machine installed with the best suitable kernel found through the controlled experiment, namely a preempt\_rt real-time Linux kernel. Fig. 4 presents the results from executing the uncontrolled experiment on the self-driving truck with an applied load produced by all software components used for its self-driving capabilities. The goal is to understand how Docker impacts the time critical scheduling precision. Fig. 4A shows that on average neither a Docker nor a native execution of the experimental unit violated the specified time deadline. Fig. 4B suggests that a deployment applying native execution performs better compared to executing with a Docker container in regards to the determinism of all executions. However, the standard deviation difference between the two deployment approaches is a mere 20\µs. The effect size ($\eta^2$) of the deployment in the uncontrolled experiment is 0.5041 which can be considered a medium effect in regards to Cohen’s D.

All experimental material such as raw data, experimental units, and statistical R scripts used for extracting and processing the data presented in this section can be found online.³

³https://github.com/docker-rt-research/experimental-material
noticeably more exhausting in relation to the truck experiment as its highest standard deviation is around 7000μs while the truck’s highest standard deviation is around 60μs.

A. Threats to Validity

The four perspective of validity threats presented by Runeson and Höst [17] are discussed. In respect to construct validity, the sample applications are realized with OpenDaVINCI to ensure a high degree of software correctness and completeness, meeting the design requirements for real-time systems. For internal validity, a number of strategies are used to limit the risk of an unknown factor impacting the data collected. Namely, the execution of the sample applications is carried out by a script to ensure precise reproducibility, all peripherals such as networking are detached and data is collected via serial communication to limit additional load to the system. In respect to external validity, the results of this study can be applied to time-sensitive applications in respect to the hardware and software used. The hardware used in this study is industrial grade, making the experiment reproducible and the results relatable to similar contexts. For conclusion validity, there exists a possibility of Type I and Type II statistical errors. Due to the sample size of the data collected, Type I and Type II errors are considerable since where an increasing sample size will result in a decreasing P-value. For that reason, this study has put less emphasis on the P-value, taking a larger consideration on the effect size when evaluating the data.

VII. CONCLUSION & FUTURE WORK

A literature review and two experiments, one controlled and one uncontrolled, have been carried out to fully comprehend how an alternation of factors within the execution environment influence the execution performance of a system for a self-driving vehicle. More specifically, these experiments sought to uncover which Linux kernel is most suitable for such a context, and whether or not utilizing Docker as a technical platform for a software deployment strategy has an impact on the time critical deadlines specified for the real-time application.

Initially, the controlled experiment intended to identify the most appropriate kernel in terms of scheduling performance. The most appropriate kernel was later implemented into an uncontrolled environment of a self-driving truck, which participated in the 2016 Grand Cooperative Driving Challenge (GCDC). The research goal was to identify whether Docker is a suitable technical environment to realize continuous integration, continuous deployment, and continuous experimentation on the self-driving truck. Our results show that Docker is not the critical factor to consider when selecting an execution environment; however, the Linux kernel in use was identified as having a greater impact on the scheduling precision and input/output performance of the software.

Future research is needed to understand how Docker behaves with respect to network performance, when several components are executed from within Docker containers and there is communication between separate computer nodes. Moreover, on-road tests will be considered in future work in order to cover variables such as CPU load and memory footprint under real-life conditions.

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