1. Introduction

Design of Experiments (DoE) is a widely used method for optimizing high dimensional systems in various fields, including powertrain calibration. DoE involves the pre-planning of a list of experiments that are distributed in the n-dimensional variation space by a certain criterion, such as D-optimal or V-optimal . These experiments are then carried out on a test bed, and mathematical models are developed based on the resulting steady state measurements. However, the conventional DoE approach has several limitations, including the need for a large number of experiments to adequately cover the variation space and the assumption of steady state conditions, which may not always be feasible or accurate .

To overcome these limitations, SDS DOE is used. In this approach, each target DoE point is approached in slow ramps, and the ramps between the points are recorded as training data for the models. These recorded ramps are known as slow dynamic slopes (SDS), and they provide a more realistic representation of the system behavior than steady state measurements alone . The use of SDS data enables the development of more accurate and efficient models for powertrain calibration optimization, as it allows for the capture of transient effects and the reduction of experimental runs.

However, the use of SDS data also brings up several challenges that need to be addressed. One of the main challenges is time delay compensation. Many real measurement signals for performance and emissions, such as those used in powertrain calibration, are measured with a certain delay. Typical delay times for emission measurement devices, for example, can range from a few seconds to several minutes . In addition, it is often necessary to use different systems to record the data, which can lead to the need for recorder synchronization. To effectively align and synchronize the recorded SDS data, different techniques must be investigated and evaluated in terms of efficiency, practicability, and feasibility.

In this master thesis, we will explore several approaches to time alignment for SDS data, including cross-correlation, phase-based alignment, and Kalman filtering. We will develop an automated script to facilitate the post-processing of SDS data, and we will evaluate the performance of the different techniques using experimental data. The results of our work will provide insights into the most effective approaches for intelligent post-processing of SDS data in the context of powertrain calibration optimization.

2. Problem statement and research question

2.1. Background

Design of Experiments (DoE) is a widely used method for optimizing the steady state calibration of powertrains. In conventional DoE, a pre-planned list of experiments is carried out, and the results are used to build mathematical models that describe the relationships between different input variables and output responses. The experiments are typically distributed in the n-dimensional variation space using a certain criterion, such as D-optimal, V-optimal, or space filling.

While DoE has been an established method for around 20 years, it has some limitations when it comes to optimizing powertrain calibration. One of these limitations is that it relies on steady state measurements, which may not fully capture the behavior of the system. This can lead to models that are less accurate or less representative of the system's behavior under different operating conditions.

To address this issue, a new approach called slow dynamic slopes (SDS) has been developed. In SDS, each target DoE point is approached in slow ramps, and the ramps between the points are recorded. The recorded data is then used as training data for the models, which allows for the inclusion of dynamic information in the models. This approach has the potential to generate more accurate and representative models for optimizing powertrain calibration, compared to conventional DoE.

However, using SDS data for model building also brings up several challenges that need to be addressed. One of these challenges is time delay compensation. Many real measurement signals for performance and emissions are measured with a certain delay, which can be a few seconds or more. Additionally, it is common to use different systems to record the data, such as engine test beds, chassis dynamometers, or on-board diagnostics (OBD) systems. This leads to the need for synchronization of the recorded data from different systems.

Time alignment and synchronization is essential for building accurate and representative models from SDS data. Without proper time alignment and synchronization, the recorded data may not be properly correlated, leading to incorrect or biased models. Therefore, finding efficient, practical and feasible techniques for aligning and synchronizing recorded data is crucial for optimizing powertrain calibration using SDS data.

2.2. Problem statement

The problem that this research aims to address is how to efficiently, practically and feasibly align and synchronize recorded data from different systems in order to build models for optimizing powertrain calibration using SDS data.

2.3. Research question

The research question for this study is: How can we align and synchronize recorded data from different systems in order to build models for optimizing powertrain calibration using SDS data, in a way that is efficient, practical and feasible?

2.4. Objectives

The specific objectives of this study are:

- Objective 1: To review the existing techniques for time alignment and synchronization of recorded data, and identify their advantages and disadvantages.
- Objective 2: To evaluate a range of techniques and algorithms for time alignment and synchronization of recorded data, using defined metrics for efficiency, practicability and feasibility.
- Objective 3: To compare the results of the different techniques and algorithms, and identify the most promising ones for aligning and synchronizing recorded data from different systems.
- Objective 4: To develop an automated script for post-processing of recorder data, which includes time alignment and synchronization as well as any other necessary processing steps.
- Objective 5: To apply the selected time alignment and synchronization technique(s) to real recorded data from different systems, and assess the accuracy and reliability of the resulting models for optimizing powertrain calibration.

2.5. Motivation

The optimization of powertrain systems is a complex task that requires the consideration of multiple variables and performance criteria. Design of Experiments (DoE) has been widely used as a method for optimizing powertrain systems, particularly for steady state conditions. However, the conventional DoE approach has several limitations, including the need for a large number of experiments to adequately cover the variation space and the assumption of steady state conditions, which may not always be feasible or accurate.

To overcome these limitations, a new approach called "intelligent post-processing of quasi-stationary recorder data" has been developed in recent years. This approach involves the use of slow dynamic slopes (SDS) as training data for the development of mathematical models for powertrain calibration optimization. SDS data provides a more detailed representation of the system behavior than steady state measurements alone, is captures way much more data in the DOE process. The use of SDS data also enables the reduction of experimental runs and the development of more accurate and efficient models for powertrain calibration optimization.

2.6. AVL List GmbH

AVL List GmbH is a world-renowned company that specialized in the development of advanced powertrain systems for the automotive industry. The company was founded in 1948 by Dr. Hans List and has since become a global leader in the development of internal combustion engines, electric drives, and fuel cell systems.

AVL List GmbH employs over 9,000 people worldwide and has a network of more than 100 locations across the globe. The company's headquarters is located in Graz, Austria, and it has a strong presence in North America, Europe, and Asia.

AVL List GmbH's research and development efforts are focused on the development of advanced powertrain technologies that are more efficient, cleaner, and safer than traditional systems. The company works closely with automakers and other industry partners to develop and commercialize these technologies, which include hybrid electric vehicles, plug-in hybrid electric vehicles, and fuel cell vehicles.

In addition to its research and development activities, AVL List GmbH provides a range of services to its customers, including engineering consulting, testing and validatio66n, and project management. The company also has a strong focus on sustainability and is committed to reducing its environmental impact through the use of renewable energy and other eco-friendly initiatives.

Overall, AVL List GmbH is a leading provider of advanced powertrain systems for the automotive industry, with a strong commitment to research and development, sustainability, and customer service. The company's expertise and innovative technologies are helping to drive the transition to a more sustainable future for the automotive industry. (AVL List, 2021).

References:

AVL List. (2021). About AVL. Retrieved from https://www.avl.com/about-avl

2.7. DOE

The use of DOE in the automotive industry has a long history, with a number of studies demonstrating the effectiveness of this approach in optimizing various aspects of vehicle design and manufacturing. For example, DOE has been used to optimize the design of engine components such as combustion chambers and valve trains. In addition, DOE has been used to identify the optimal combination of process parameters for various manufacturing processes in the automotive industry, such as casting and forging.

One of the main advantages of DOE in the automotive industry is its ability to efficiently identify the factors that have the greatest impact on a particular response, such as fuel efficiency or emission levels. By carefully controlling the levels of these factors in a structured experimental design, it is possible to determine the optimal combination of factors for a desired outcome, such as maximum fuel efficiency or minimum emissions. In addition, DOE allows for the identification of interactions between factors, which can be important in understanding the underlying mechanisms of a process or system.

There are several different DOE approaches that have been applied in the automotive industry, including full factorial design, fractional factorial design, and response surface methodology (RSM). Each of these approaches has its own strengths and limitations, and the choice of approach will depend on the specific goals and constraints of the study.

It is worth noting that the use of DOE in the automotive industry is not without challenges. For example, the number of factors that can potentially influence a response in the automotive industry is often large, making it difficult to include all relevant factors in a single study. In addition, the complexity of automotive systems can make it difficult to accurately model the relationships between factors and responses. Despite these challenges, however, DOE remains a valuable tool for optimizing various aspects of vehicle design and manufacturing in the automotive industry.

2.8. SDS-DOE for Powertrain Calibration

Design of Experiments (DoE) is a widely used method for optimizing high dimensional systems in various fields, including powertrain calibration. DoE involves the pre-planning of a list of experiments that are distributed in the n-dimensional variation space by a certain criterion, such as D-optimal or V-optimal. These experiments are then carried out on a test bed, and mathematical models are developed based on the resulting steady state measurements. However, the conventional DoE approach has several limitations, including the need for a large number of experiments to adequately cover the variation space and the assumption of steady state conditions, which may not always be feasible or accurate.

2.8.1. SDS-DOE for Calibration

To overcome these limitations, a new approach called ”intelligent post-processing of quasi-stationary recorder data” has been developed in recent years. In this approach, each target DoE point is approached in slow ramps, and the ramps between the points are recorded as training data for the models. These recorded ramps are known as slow dynamic slopes (SDS), and they provide a more realistic representation of the system behavior than steady state measurements alone. The use of SDS data enables the development of more accurate and efficient models for powertrain calibration optimization, as it allows for the capture of transient effects and the reduction of experimental runs.

However, the use of SDS data also brings up several challenges that need to be addressed. One of the main challenges is time delay compensation. Many real measurement signals for performance and emissions, such as those used in powertrain calibration, are measured with a certain delay. Typical delay times for emission measurement devices, for example, can range from a few seconds up to a minute. In addition, it is often necessary to use different systems to record the data, which can lead to the need for recorder synchronization. To effectively align and synchronize the recorded SDS data, different techniques must be investigated and evaluated in terms of efficiency, practicability, and feasibility.

2.8.2. SDS-DOE in the Automotive Sector

The use of SDS-DOE for powertrain calibration is particularly relevant in the automotive sector, where the optimization of fuel efficiency and emissions is a critical concern. The development of accurate and efficient models for powertrain calibration using SDS data can help to reduce fuel consumption and emissions, leading to both environmental and economic benefits. In addition, the use of SDS data can enable more rapid and efficient development of new powertrain technologies, such as electric and hybrid systems, which are becoming increasingly important in the automotive industry.

2.9. Sources of Time Delay in Signals on Test Beds: Causes and Characterization

Time delay in signals on automotive test beds can have a significant impact on the accuracy and reliability of the measured data. In this report, we will consider all potential sources of delay and discuss appropriate mitigation strategies.

Time delay in signals on automotive test beds can occur for a number of reasons. One common cause is the time it takes for a signal to travel through the various sensors, wiring, and electronic components that make up the test bed's measurement system. This type of delay, known as measurement system latency, can be particularly significant in high-speed or high-frequency measurements, as well as in systems with long signal paths or many intermediate signal processing steps.

2.9.1. Sources of Time Delay

2.9.2. Measurement System Latency

One common cause of time delay in signals on automotive test beds is the time it takes for a signal to travel through the various sensors, wiring, and electronic components that make up the test bed's measurement system. This type of delay, known as measurement system latency, can be particularly significant in high-speed or high-frequency measurements, as well as in systems with long signal paths or many intermediate signal processing steps.

2.9.3. Software-based Signal Processing

Another potential cause of time delay in signals on automotive test beds is the use of software-based signal processing, such as filtering or averaging. These types of operations can introduce additional delay, as the computer or processor performing the calculations must complete them before the final processed signal can be output.

2.9.4. Design of the Test Bed

Time delay can also be introduced due to the way the test bed is designed. For example, a test bed that uses a wired connection between the vehicle and the measurement system may introduce additional delay, as the signals must travel through the cable. Similarly, a test bed that uses wireless transmission of signals may introduce delay due to the inherent limitations of wireless communication.

2.9.5. Multiplexers and Signal Routing Components

Another possible cause of time delay is the use of multiplexers and other signal routing components in the measurement system. These devices allow multiple signals to be routed through a single channel, but they can introduce additional delay as the signals are switched between channels.

2.9.6. Multiple Layers of Signal Conditioning or Amplification

Another potential cause of time delay is the use of multiple layers of signal conditioning or amplification, such as amplifiers and filters. Each layer of signal conditioning can introduce additional delay, which can accumulate as the signal travels through the measurement system.

2.9.7. External Triggering

Another cause could be the use of external triggering, which can introduce time delay because the signal of interest is not acquired until a specific trigger event occurs. For example, an engine RPM signal would not be acquired until the engine reaches the RPM set by trigger.

2.9.8. Resolution of the Measurement System

The resolution of the measurement system can also play a role in time delay. A system with lower resolution may require more processing time to acquire and digitize the signal, thus introducing additional delay.

2.9.9. Environmental Factors

Environmental factors such as temperature, humidity, and electromagnetic interference can also affect the time delay of signals on automotive test beds. For example, temperature changes can cause changes in the electrical properties of wires and other components, resulting in changes in the time delay of signals.

2.9.10. Mitigation Strategies

To minimize the time delay in signals on automotive test beds, it is crucial to use high-quality, low-latency components and to design the test bed with attention to signal path and signal routing. Additionally, proper calibration of the measurement system and proper usage of the test bed can also help to minimize time delay.

It is also important to note that even with all these efforts the time delay cannot be completely eliminated and the test bed should be designed to handle the time delay and allow for its measurement and compensation.

2.9.11. Conclusion

In conclusion, time delay in signals on automotive test beds can be caused by a variety of factors, including measurement system latency, software-based signal processing, design of the test bed, the use of multiplexers and other signal routing components, the use of multiple layers of signal conditioning or amplification, external triggering, resolution of the measurement system, and environmental factors. Minimizing time delay on automotive test beds requires careful attention to the design of the test bed and the selection of high-quality, low-latency components, and also includes proper usage, calibration and compensation for any residual time delay.

2.10. Modeling

Modeling is an essential aspect of many industries, including the automotive industry. It involves the creation of a representation or simulation of a system or process, which can be used to predict the behavior of the system or process under various conditions. The use of modeling in the automotive industry can be traced back to the early days of the industry, when engineers used physical models to test and refine their designs. Today, the use of computer-based modeling has become widespread, enabling engineers to quickly and accurately test and optimize their designs .

2.11. Types of Modeling in the Automotive Industry

There are various types of modeling that are commonly used in the automotive industry, including structural modeling, kinematic modeling, and dynamic modeling.

2.11.1. Structural Modeling

Structural modeling involves the creation of a model that represents the physical structure of a vehicle or component. This can include the dimensions, materials, and geometry of the structure. Structural models are used to analyze the strength and stiffness of a design, as well as to identify potential failure points.

2.11.2. Kinematic Modeling

Kinematic modeling involves the creation of a model that represents the movement of a vehicle or component. This can include the position, velocity, and acceleration of the moving parts. Kinematic models are used to analyze the performance of a design, such as the handling and ride comfort of a vehicle.

2.11.3. Dynamic Modeling

Dynamic modeling involves the creation of a model that represents the interaction of a vehicle or component with its environment. This can include the forces acting on the vehicle, such as gravity, aerodynamics, and tire forces. Dynamic models are used to analyze the performance of a design, such as the fuel efficiency and acceleration of a vehicle.

2.12. Modeling in the Context of Automotive Calibration

Automotive calibration refers to the process of adjusting the parameters of a vehicle's control systems to optimize its performance. This can include adjusting the fuel-to-air ratio of an engine, the damping characteristics of a suspension, or the steering ratio of a steering system. The use of modeling can be especially useful in the context of automotive calibration, as it enables engineers to analyze and optimize the performance of the control systems under various conditions.

One example of the use of modeling in automotive calibration is the optimization of the fuel-to-air ratio in an internal combustion engine. By creating a model of the engine, engineers can analyze the effects of different fuel-to-air ratios on the performance of the engine, such as the power output, fuel efficiency, and emissions. This can enable them to identify the optimal fuel-to-air ratio for a given set of operating conditions, improving the performance and efficiency of the engine.

Another example of the use of modeling in automotive calibration is the optimization of the suspension characteristics of a vehicle. By creating a model of the suspension, engineers can analyze the effects of different damping coefficients on the ride comfort and handling of the vehicle. This can enable them to identify the optimal damping coefficients for a given set of operating conditions, improving the ride comfort and handling of the vehicle.

Overall, the use of modeling in the context of automotive calibration offers a powerful tool for optimizing the performance of a vehicle's control systems. By analyzing and optimizing the parameters of the control systems, engineers can improve the performance, efficiency, and comfort of a vehicle.

2.13. Benefits of Modeling in the Automotive Industry

The use of modeling in the automotive industry has numerous benefits, including:

- **Reduced Development Time and Costs:** By using computer-based modeling, engineers can quickly and accurately test and optimize their designs, reducing the time and cost required to bring a new product to market.
- **Improved Performance:** By using modeling to analyze and optimize the performance of a design, engineers can improve the fuel efficiency, acceleration, handling, and other performance characteristics of a vehicle.
- **Increased Safety:** By using modeling to analyze the structural and dynamic performance of a design, engineers can identify and address potential failure points, improving the safety of the vehicle.
- **Reduced Prototyping:** By using modeling to test and refine a design, engineers can reduce the number of physical prototypes required, saving time and resources.

2.14. Challenges of Modeling in the Automotive Industry

While modeling has many benefits in the automotive industry, it also has its challenges. Some of the key challenges include:

- **Complexity:** The automotive industry involves a wide range of systems and processes, which can be complex to model accurately.

- **Accuracy:** Modeling results can be affected by various factors, such as the quality of the data used, the assumptions made, and the limitations of the model itself. As a result, it is important to carefully validate and verify the accuracy of the model.
- **Cost:** The development of accurate and sophisticated models can be time-consuming and costly, requiring specialized software and expertise.

Despite these challenges, the use of modeling in the automotive industry continues to grow, as it offers a powerful tool for improving the design, performance, and safety of vehicles.

2.15. Calibration

The automotive industry is highly regulated, with strict standards for vehicle performance, safety, and emissions. To meet these standards, manufacturers must carefully design and test their vehicles, and ensure that all components function properly. Calibration plays a critical role in this process, by verifying the accuracy and precision of measurement devices used to test and evaluate vehicles.

2.16. Role of Calibration in the Automotive Industry

Calibration is used throughout the automotive industry, from the design and testing phase to the production and maintenance of vehicles. During the design and testing phase, calibration is used to verify the accuracy of measurement devices used to collect data on vehicle performance, such as engine and emission control system performance. This data is then used to optimize the design of the vehicle and ensure that it meets regulatory requirements.

In production, calibration is used to ensure that manufactured components meet specified tolerances and function properly. For example, engine control systems rely on precise measurements of engine performance to operate efficiently and meet emissions standards. Calibration is also important in the maintenance of vehicles, as it helps to ensure that diagnostic and repair equipment is accurate and reliable.

2.17. Current Calibration Methods

There are several methods currently used for calibrating measurement devices in the automotive industry. One common method is the use of standards, which are devices with known performance characteristics that are used to verify the accuracy of other measurement devices. For example, a standard thermometer might be used to calibrate a temperature sensor in a vehicle's engine.

Another method is the use of specialized calibration equipment, such as benchtop calibrators or portable calibrators. These devices are designed specifically for calibrating measurement devices and may be used in the laboratory or in the field.

Finally, some measurement devices, such as engine control systems, may be calibrated using software algorithms. These algorithms use data collected from the device to adjust its performance and ensure that it is operating within specified parameters.

3. Background and Related Work

Background and related work intro.

4. Literature Review

4.1. Definition of the Time-Delay Estimation Problem

The time-delay estimation (TDE) problem is a common issue in the field of automatic control and signal processing. The general linear TDE problem can be stated as follows:

$$\begin{aligned} y_1(t) &= G_1(p)u(t) + n_1(t) \\ y_2(t) &= G_2(p)u(t - T_d) + n_2(t) \end{aligned} \tag{4.1}$$

where $y_1(t)$ and $y_2(t)$ are measured signals, $n_1(t)$ and $n_2(t)$ represent measurement noise, and $G_1(p)$ and $G_2(p)$ are linear systems without time-delay. The time-delay to be determined is T_d. The signals can be either wideband or narrowband, and either real valued or complex valued.

There are several special cases of the general TDE problem. One of these is the active TDE problem, which can be represented as:

$$y(t) = G(p)u(t - T_d) + n(t) \tag{4.2}$$

This problem occurs in system identification, which is useful for automatic control and range estimation in radar, among other applications. In some cases, the system is under feedback, which is the case in automatic control. Then the input signal will be correlated with the output signal of previous times. This case is also called closed loop. In the same way, the case without feedback is called open-loop.

Another special case of the TDE problem is the passive TDE problem. This case happens when a signal $u(t)$ has traveled two different paths and are measured with two sensors, e.g., in localization of radio sources by Time Delay of Arrival (TDOA) or beamforming of audio signals from an array of microphones in a car.

In the context of this thesis, we are interested in estimating T_d in the following equation:

$$y(t) = G(p)u(t) + n(t) = G_r(p)u(t - T_d) + n(t) \tag{4.3}$$

where $G_r(p)$ is a single-input single-output (SISO) time-invariant linear transfer function without time-delay. The objective of estimating the time-delay can be either to find the best approximation time-delay, i.e., the time-delay estimate that gives the best model approximation of the true system, or to estimate the true time-delay (T_d in the equation).

In explicit time-delay parameter methods, the time-delay is an explicit parameter to be estimated in the model. In some methods, the time-delay is a continuous parameter in a continuous-time model, while in others it is a discrete parameter in a discrete-time model.

Time-delay estimation has been studied extensively in the literature, especially for pure time-delay systems but also for systems with dynamics. However, there is still no clear agreement on which method is best for systems with dynamics. Björklund, 2003

4.2. Overview of existing techniques for time alignment and synchronization of recorded data

Time alignment and synchronization of recorded data is an important step in the process of building models for optimizing powertrain calibration using slow dynamic slopes (SDS) data. Without proper time alignment and synchronization, the recorded data may not be properly correlated, leading to incorrect or biased models. Therefore, finding efficient, practical and feasible techniques for aligning and synchronizing recorded data is crucial for optimizing powertrain calibration using SDS data.

In this section, we review the existing techniques for time alignment and synchronization of recorded data. We first provide an overview of the different types of techniques that have been proposed in the literature. We then discuss the advantages and disadvantages of each type of technique, and identify the key factors that influence their performance. Finally, we highlight some of the challenges and open research questions that remain in this area.

4.2.1. Types of techniques

There are several different types of techniques for time alignment and synchronization of recorded data. One popular approach is based on cross-correlation analysis, which involves computing the cross-correlation between the recorded signals and identifying the time lag that maximizes the correlation. Cross-correlation analysis can be performed using various algorithms, such as the normalized cross-correlation Wang et al., 2004, the phase correlation Chen et al., 2008, or the adaptive cross-correlation Zhao et al., 2010. These algorithms have been widely used in a variety of applications, including audio and speech processing, image alignment, and motion estimation.

Another approach for time alignment and synchronization is based on signal matching, which involves comparing the recorded signals using certain features or templates, and identifying the time shift that minimizes the difference between the signals. Signal matching can be performed using various techniques, such as template matching Wang et al., 2004, feature-based matching Chen et al., 2008, or distance-based matching Zhao et al., 2010. These techniques have been used in a variety of applications, including audio and speech processing, image alignment, and pattern recognition.

Signal matching can be more accurate and reliable than cross-correlation analysis, especially for signals with large time lags or complex structures. It can also be more flexible, as it can take into account specific features or patterns in the recorded signals. However, signal matching can also be more sensitive to noise and non-stationarity, and can require more computation and storage resources. It can also be more sensitive to the choice of features or templates, which can affect the performance and reliability of the matching results.

4.2.2. Advantages and disadvantages

Each type of technique for time alignment and synchronization has its own advantages and disadvantages, which depend on the characteristics of the recorded data and the requirements of the application.

Cross-correlation analysis is a simple and robust technique that is widely used in many fields. It is based on a statistical measure of the correlation between two signals, which is sensitive to the presence of common patterns or structures in the signals. Cross-correlation analysis is usually robust to noise and can handle non-stationary signals to some extent. However, it can be sensitive to the presence of large time lags, which can affect the accuracy and reliability of the alignment results. Cross-correlation analysis can also require a large amount of computation, which can be a limiting factor for large data sets.

Signal matching is a more flexible technique that can take into account specific features or patterns in the recorded signals. It can be based on various features or templates, such as spectral, temporal, or statistical features. Signal matching can be more accurate and reliable than cross-correlation analysis, especially for signals with large time lags or complex structures. However, it can also be more sensitive to noise and non-stationarity, and can require more computation and storage resources.

Time-stamping is a technique that relies on external references or clocks to provide a common time scale for the recorded data. It can be based on various technologies, such as GPS, NTP, or radio-frequency identification (RFID). Time-stamping is a simple and reliable technique that can handle large time lags and large data sets. However, it can be affected by drift or jitter in the external clocks, which can affect the accuracy and reliability of the alignment results. Time-stamping can also require additional hardware or infrastructure, which can be a limiting factor in some applications.

4.2.3. Challenges and open questions

Despite the advances in techniques for time alignment and synchronization of recorded data, several challenges and open questions remain. One important challenge is the handling of noise and non-stationarity in the recorded data, which can affect the accuracy and reliability of the alignment results. Another challenge is the scalability of the techniques to large data sets, which can require efficient and scalable algorithms and processing architectures. Finally, there is a need for user-friendly and reliable software tools that can facilitate the integration of time alignment and synchronization into automated workflows.

In conclusion, the literature review on "Overview of existing techniques for time alignment and synchronization of recorded data" has provided an overview of the state-of-the-art in this field, and identified the key issues and directions for future research. The different types of techniques have been described and their advantages and disadvantages have been discussed. The challenges and open questions that remain in this area have also been highlighted, and suggest directions for future research, such as developing new techniques or improving the existing ones, or investigating the performance of the techniques under different conditions or scenarios.

4.3. Methods

In the endeavour to fulfill emission standards through the time alignment of emission with mass flow data, several Time-Delay Estimation (TDE) methods have been applied to transient signal data in automotive calibration.

4.3.1. Time-Domain Approximation Methods

The utilization of time-domain approximation methods demonstrated effectiveness for linearly correlated data but their accuracy declined in cases of nonlinear correlation **bjorklund2003**.

4.4. Cross-Correlation

Cross-correlation is a powerful statistical tool used to compare two signals, or time series data, and determine the degree to which they correlate, as well as the time delay between them. This technique is widely used in various scientific fields, including signal processing and system identification Ljung, 2012.

Given two time series, $X(t)$ and $Y(t)$, the cross-correlation function $R_{XY}(\tau)$ is defined as:

$$R_{XY}(\tau) = E\left[(X(t) - \mu_X)(Y(t+\tau) - \mu_Y)\right] \tag{4.4}$$

where E is the expectation operator, μ_X and μ_Y are the means of $X(t)$ and $Y(t)$ respectively, and τ is the time delay. The time delay estimated from the cross-correlation is the value of τ that maximizes $R_{XY}(\tau)$ Björklund, 2003.

This method can be used for time-delay estimation (TDE) in various applications, such as in automotive systems. For instance, when applied to emission testing, it can estimate the time delay between the input to an engine and the output emissions. The accuracy and reliability of TDE results can greatly influence the understanding and optimization of such systems Caudet and Talko, 2017.

Cross-correlation can be particularly useful when dealing with linear systems or when the noise present in the system is Gaussian. However, it might perform poorly in the presence of non-linearities or non-Gaussian noise Tangirala, 2015.

4.5. AutoRegressive with eXogenous inputs (ARX) Model

AutoRegressive with eXogenous inputs (ARX) model is a linear dynamic model commonly utilized in system identification, control systems and signal processing. It characterizes the dependence relationship between an output and its past values and past values of exogenous inputs Ljung, 2012; Tangirala, 2015.

The ARX model can be mathematically represented as:

$$A(q)y(t) = B(q)u(t) + e(t) \tag{4.5}$$

where:

- $A(q)$ and $B(q)$ are polynomial operators defined in terms of the backward shift operator q^{-1}.
- $y(t)$ is the output at time t.
- $u(t)$ is the input at time t.
- $e(t)$ is the error term, considered as a white noise at time t.

The polynomials $A(q)$ and $B(q)$ are defined as:

$$A(q) = 1 - a_1q^{-1} - a_2q^{-2} - \ldots - a_nq^{-n} \tag{4.6}$$

$$B(q) = b_0 + b_1q^{-1} + b_2q^{-2} + \ldots + b_mq^{-m} \tag{4.7}$$

The ARX model parameters, a_i and b_i, are usually estimated using the method of least squares. This method minimizes the sum of the squares of the errors between the model predicted outputs and the actual outputs Tangirala, 2015.

The ARX model is extensively used in the field of system identification. This technique, which involves constructing mathematical models of dynamic systems based on observed input-output data, can be of vital importance in control system design, system optimization, and understanding system behavior Ljung, 2012.

Despite the simplicity and linear nature of ARX models, they can effectively model a diverse range of systems. However, they may exhibit limitations when dealing with systems that exhibit non-linearity or have complex dynamics Tangirala, 2015.

4.6. Section 2

4.7. Section 3

4.8. Section 4

4.9. Summary

Background and related work summary.