Masterarbeit

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Thema: FAIR Sensor Health Monitoring of Flight Test Data

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Master Thesis

for Ms./Mrs. Cand.-Ing. Erika Mustermann
Matriculation number: 081511

Topic: FAIR Sensor Health Monitoring of Flight Test Data.

The start of production for series production represents a major uncertainty and cost factor for both manufacturers and users of automated production systems. In particular, the poor planning of the production start-up requires new approaches that support the early safeguarding of the functionality and performance of automated production systems. Within the BMBF joint project Ramp-Up/2, the step from two-dimensional alphanumeric planning to an integral 3D-based digital verification of plant development and commissioning is aimed at. For this purpose, a kinematic 3D model of the production plant and all control components (NC/PLC) are simulated by virtual NC/PLC software modules and the mechanical behaviour of a machine is depicted by the Siemens Machine Simulator (MS). Based on this virtual production system, the aim of the plant development is to enable a preliminary verification of the production control software. In doing so, technical errors as well as operating and software errors are to be simulated and the reaction of the control software is to be analysed by means of diagnostic tools.

Within the scope of the work, concepts and tools are to be developed which enable the testing of the functionality of a production control software. In particular, the following questions are to be dealt with: which test cases can occur, how errors/tests can be reproduced, which data are necessary for the clear diagnosis of an error and to what extent tools can be used for error correction. Based on these considerations, a concept for information visualization is to be developed and realized exemplarily. The information content as well as the temporal sequence of the information flow within the production control software should be mapped and the possibility should be provided to reset the system into a freely defined state (time). The developed concepts are to be realized exemplarily on the basis of the control software cosmos4. The functionality and performance of the developed tools will be verified using an example scenario in the Integrated Manufacturing and Assembly System (IFMS) of the WZL.

In detail, the following subtasks have to be solved:

- Introduction with the leading software cosmos4
- Development of a comprehensive concept for error diagnosis and correction
- Exemplary realization of a scalable information visualization and recovery
- Documentation of the work

Prof. Dr.-Ing. Robert Schmitt

I Contents

II Acronyms

Symbol	Unit	Description
a_e	mm	Width
a_p	mm	Cutting depth
t		Number of teeth [Note: Sorting is alphabetical]
α		angle

Abbreviation	Description
DP	Polycrystalline diamond
ADC	Analog Digital Converter

III List of Figures

IV List of Tables

1 Introduction

FAIR Sensor Health Monitoring of Flight Test Data

- mention FAIR. How is this work implementing FAIR principles - how and what is sensor health monitoring? - explain flight test data. What is it and where does it come from? - which data is used - in which context does it get used?

1.1 What we want to do

Filtering out sensor errors is the goal of this thesis. As described in figure 1.1 the error can be imagined as a disturbance added upon the original sensor value.

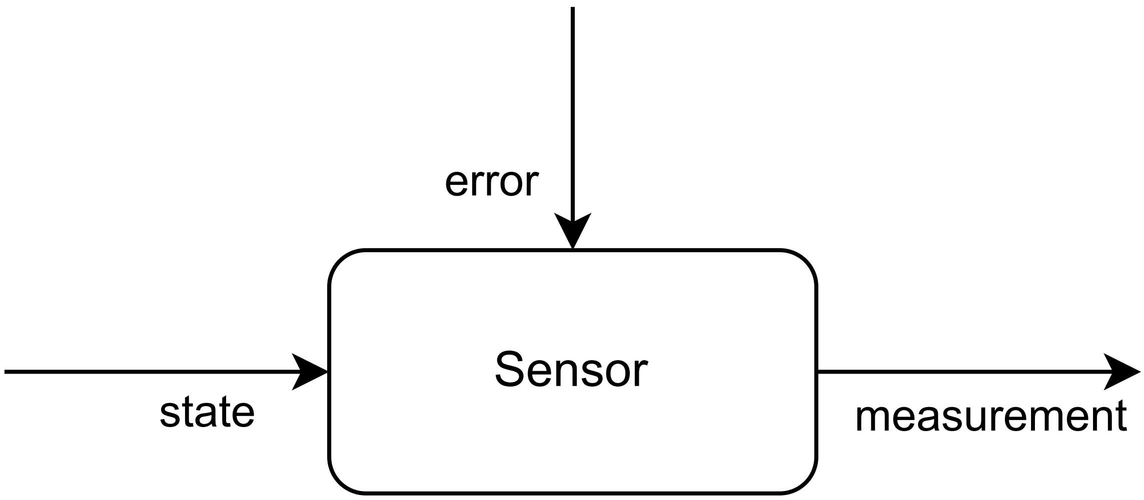


Figure 1.1: Sensor Signal

The following chapter is a description for using Latex. The most basic steps will be explained including citation, adding figures, making tables, ... and so on. If you have already used Latex before or are familiar with the process, this chapter might not be interesting for you. But if you are new to the concept or need a refresher, the following might be useful to you.

Not everything might be apparent if you are reading this text as a PDF-file. For further understanding, read the actual latex-file (go to 01-chapters/ch1-intro.tex).

1.2 Getting started with Latex

If you haven't worked with Latex yet, you first have to install a few things. Go to the README.md file and follow the instructions.

1.3 Add a new chapter

To add a new chapter, right-click on 01-chapters and add a new document. In order for it to be displayed in your PDF-file, it first has to be included. Go to main.tex and include it, as shown.

1.4 Including figures

The command to include a graphic is "\includegraphics". To add a description use the following command "\caption{your Text}". However this command can only be used in a specific surrounding (marked by "\begin{figure}" and "\end{figure}".

The surrounding has also other functions, which you can use; for futher information look up the following website: `https://de.overleaf.com/learn/latex/Inserting_Images`

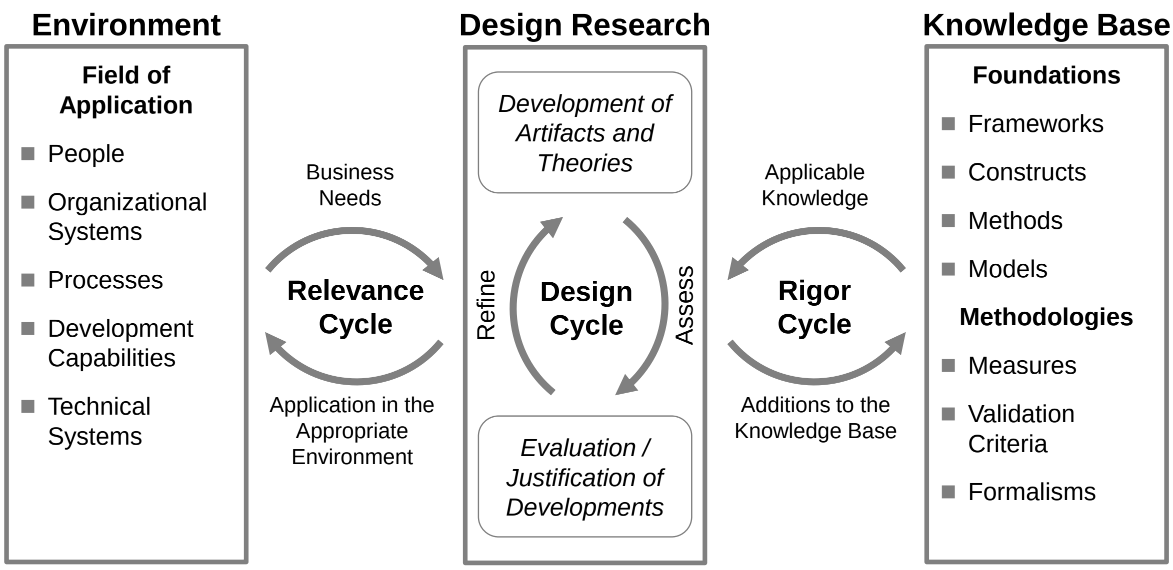


Figure 1.2: TMP: Design science research framework original image [based on KHAL22, p. 80].

1.5 Including tables

The compilation of a table can be difficult, especially if everything needs to be consistent. In order to simplify this task, try using the following website: `https://www.tablesgenerator.com/` It provides a simple user interface, which generates the table for you.

The "label"-command is for referencing the table or graphic in your text: Table 1.1.

Table 1.1: Comparison of different desserts.

hier soll was stehen	gut	neutral	schlecht	k.A.
Käsekuchen				
Schokotorte				
Brombeereis				

1.6 Citation

In order to cite a reference, it first has to be included to the Bib. To do so, follow the instructions of the following link: `https://www.youtube.com/watch?v=kbvf01ExKVU`

1.7 Acronyms

For adding something to the Acronyms, go to "en" or "de" (depending on you using german or english) and select "frontmatter.tex". In this document you will find the table of Acronyms.

2 State of the art and a theoretical Background

Chapter 2 introduces the theoretic baselines for data acquisition, data metrics as well as standardized data formats in which to save metadata.

Topics to consider when starting the Sensor Health Monitoring process are mainly that of providing a structured overview of the Sensor Metadata which in itself consists of many layers as a dynamically generated set of metadata is desired. This should be able to accomodate changing Data Acquisitioning (DAQ) System configuration changes. Consideration is given to the SOIL data model and its' ability to accomodate the many demands that are expected of sensor data management. [BODE21] The second major part to consider is that of physical crossrelations and d̈eep checksẅhich are a experimental mode of checking for inconsistencies among the data. Major research and implementation work shall go into developing a dynamic model that is generated from the data and then checks back upon the data for possible discrepancies. This approach is chosen as it is estimated to be the most structured approach for a first prototype.

This topic shall give an overview over the state of the art technology as well as systems and describe the systems employed by this work. Structuring the data

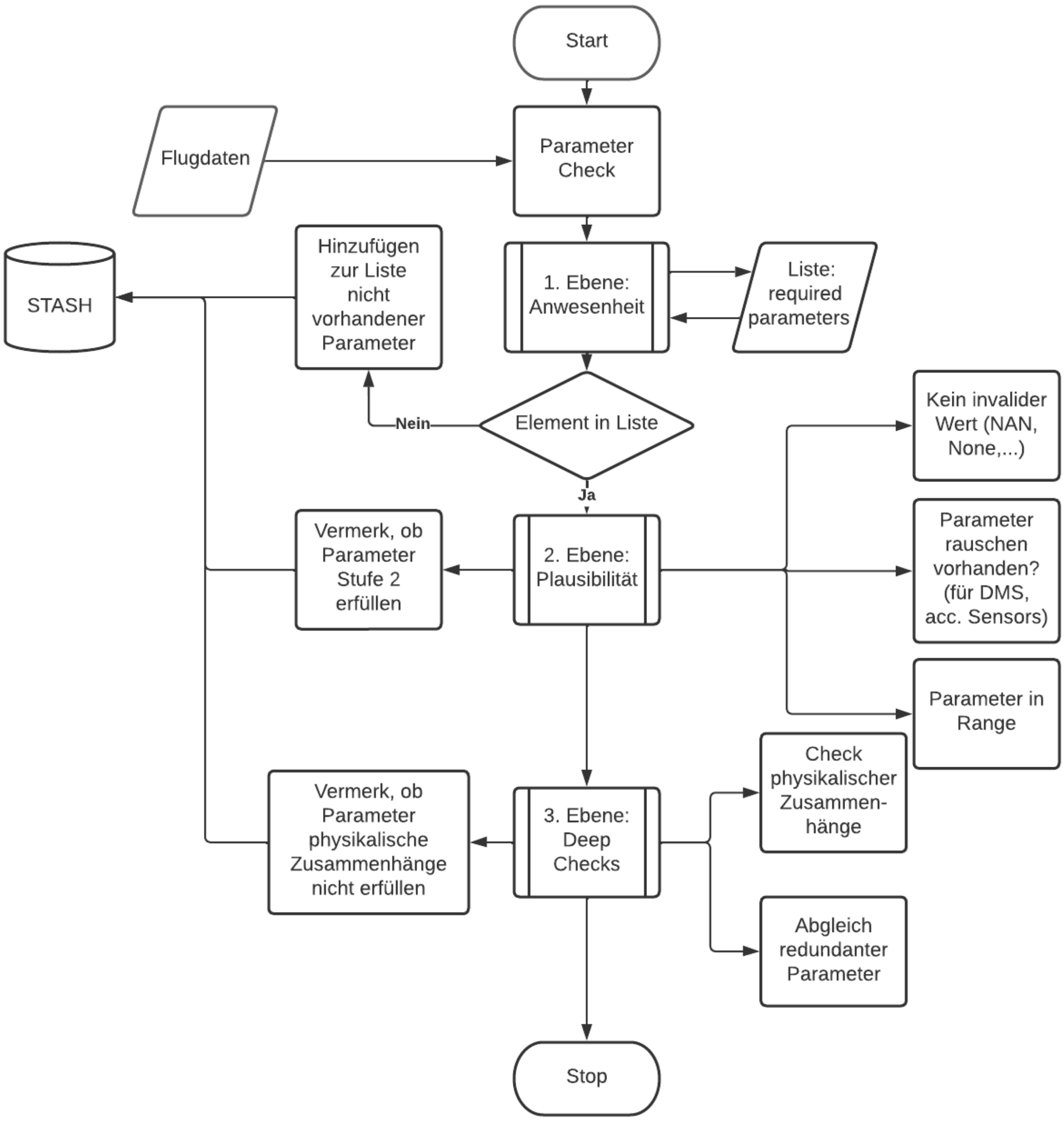

Start
Flugdaten
Parameter Check
Hinzufügen zur Liste nicht vorhandener Parameter
STASH
1. Ebene: Anwesenheit
Liste: required parameters
Nein
Element in Liste
Ja
Kein invalider Wert (NAN, None,...)
Vermerk, ob Parameter Stufe 2 erfüllen
2. Ebene: Plausibilität
Parameter rauschen vorhanden? (für DMS, acc. Sensors)
Parameter in Range
Check physikalischer Zusammen-hänge
Vermerk, ob Parameter physikalische Zusammenhänge nicht erfüllen
3. Ebene: Deep Checks
Abgleich redundanter Parameter
Stop

Figure 2.1

2.1 Data Format, FAIR

Originating from a dutch alliance of biotechnology institutes in 2015, the FAIR Guiding principles emerged in 2016 as a general best practice guide for research data, referencing best practices

FAIR principles have been published in 2016 by the source here. They set the foundation for a standardized and open data culture. Within these principles values like open access for data, findable and well tagged datasets, interoperable data by using standardized formats and or semantics (define semantics as well) which guarantee a reusability of data to generate a sustainable process for data usage. Effectively meaning that similar experiments do not have to be performed multiple times when well tagged and formatted data is freely available.

json file format (FAIR-principles, INST-DLR, SOIL)

Explain which means are taken to guarantee an architecture throughout the work that ensures an implementation of the FAIR principles and the V-model. Architecture of the JSON-Tree structure and which data is inserted where.

-modern data management principles (storage not as important as readability)

Comparison with existing data structures. Implementation into existing architecture

–> Chosen Data Model, Semantics

2.2 Definitions

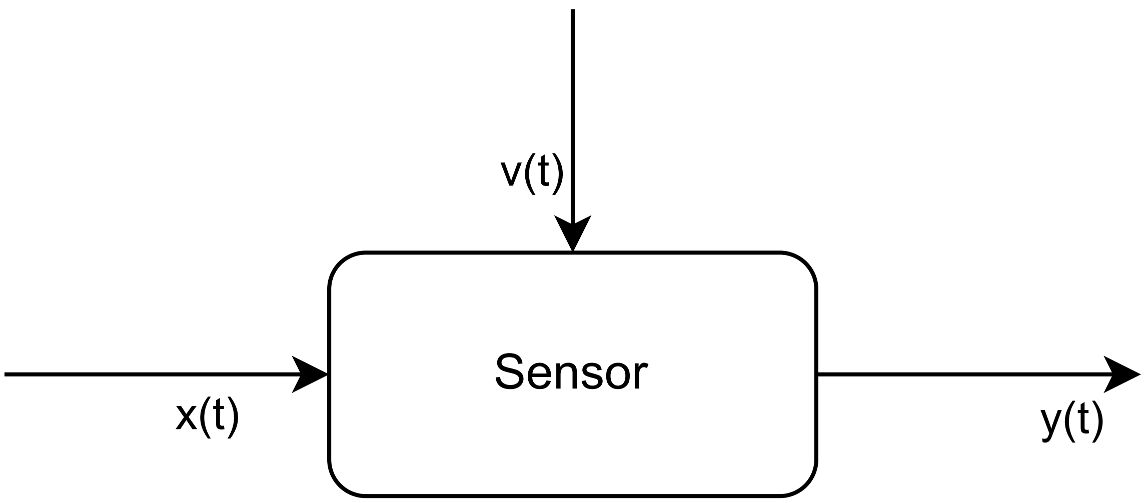


Figure 2.2: Sensor Signal with control systems

Unambiguous terms are needed to provide clear information within the sensor health monitoring data structure. This is needed in regards to basic terms like semantics as well as data metrics. In the following, industry standards and definitions are collected to accompany this work.

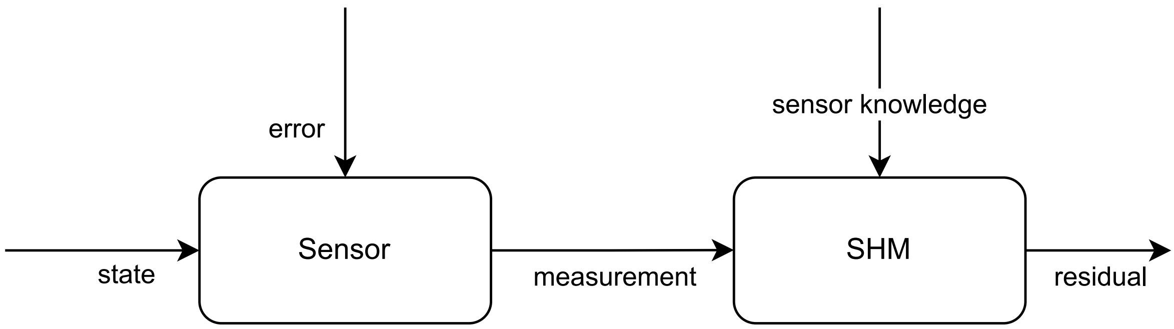


Figure 2.3: Sensor Signal Filter

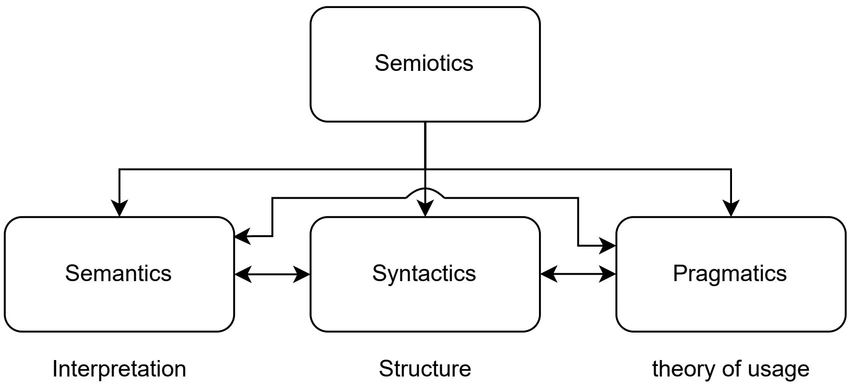


Figure 2.4: Semiotics, according to Kutschera [KUTS75] and Shoemaker and Blackburn [SHOE87]

2.2.1 Semantics

Semantics are defined in various way by various people. One definition that has found some acceptance is the definition by Metzlers Lexikon which relies on theories by Blackburn and Kutschera. [SHOE87; KUTS75]

First off, semiotics from the greek , semeion for sign, describes the theory of signs and their usage. Semiotics is divided into the areas semantics, syntactics and pragmatics. Within the definition at hand syntactics is given as the internal structure of signs within sign systems, pragmatics are defined as the theory of sign usage effectively thinking about how interaction with signs works. Finally, semantics define the relationship between signs and described objects. They work by allocating a structure/model to a predefined expressions

2.2.2 Metadata descriptors

No clear, fully unambiguous definition exists for most of following terms. However some assumptions have been made by e.g. isermann et al[ise97] within trends and apps.. in discussion with vdi/vde committees and the reliability, availability and maintainability (RAM) dictionary. Definitions are classified as:

deviation: difference to a reference value

- **states and signals (chapter 2.2.3)**
- **functions (chapter 2.2.4)**

- **models (chapter 2.2.5)**
- **system properties (chapter 2.2.6)**

2.2.3 States and Signals

Properties of signals

descriptor	description
fault	unpermitted deviation of one subset of the system
failure	permanent interruption
malfunction	intermittent regularity
disturbance	unknown, uncontrolled input
perturbation	input, leading to temporary departure from steady state
error	deviation between measurement and true, specified, theoretically correct value $y_e = \bar{y} - y$
residual	fault indicator based on deviations between measurements and model-based calculations $\hat{y} = \bar{y} - y_m$

Table 2.1: states and signals

2.2.4 functions

descriptor	description
fault detection	determination fault presence
fault isolation	Determination fault properties: kind, location, time of detection
fault identification	determination of size and time-variant behaviour of fault
fault diagnosis	includes fault detection, isolation, identification
monitoring	real-time determination of possible physical conditions and recognition and indication of behavioural ano
Supervision	monitoring and taking actions to maintain operation during faults
protection	means by which potentially dangerous behaviours are suppressed if possible or how consequences are avo

Table 2.2: functions

2.2.5 models

2.2.6 system properties

data quality: reliability (isermann) availability (isermann) accuracy

descriptor	description
quantitative	describe system in quantitative mathematical terms
qualitative	describe system in causalities and if-then rules
diagnostic	link specific inputs (symptoms) to outputs (faults)
analytical redundancy	determine a quantity in an additional way by using a mathematical process model

Table 2.3: models

descriptor	description
MTTF=$1/\lambda$	Mean time to failure
λ	rate of failure
MTTR $= 1/\mu$	mean time to repair
μ	rate of repair

Table 2.4: system properties

descriptor	description
reliability	ability to perform a function, measure $MTTF$, with λ as rate of failure per hour
safety	ability of a system not to cause danger to persons, equipment and environment
availability	$A = \frac{MTTF}{MTTF+MTTR}$

Table 2.5: system properties

2.2.7 Integrity, Reliability and Validity based on GNSS or NORMS von Lars

Data according to ISO 8000 cite [ISO22] iso5725: -accuracy(validity)+precision(reliability) Also see precision and accuracy definition [SMIT, S.33ff.]

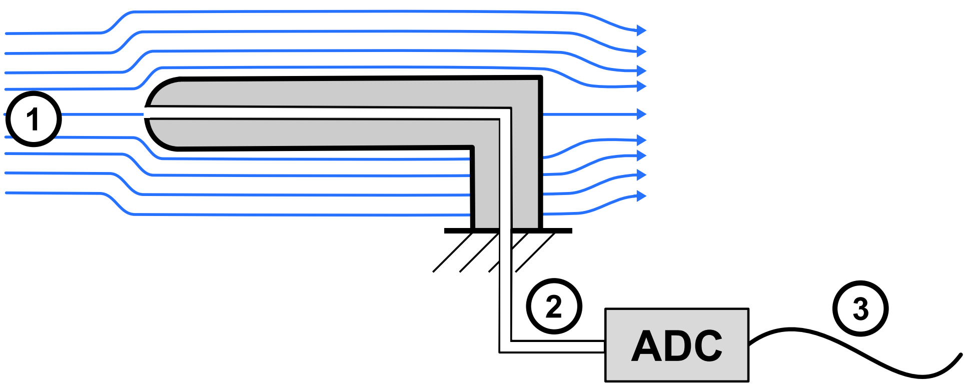
Other measures for various positioning systems are found in FAA [FAA08]. Also, similar definitions are found as defined in **isermann_fault-diagnosis_2011empty citation** $Reliability = 1 - Probability_{Failure}$ [FAA08, B.1.5]

B.1.10: Integrity: Display when system should not be used due to potential errors.

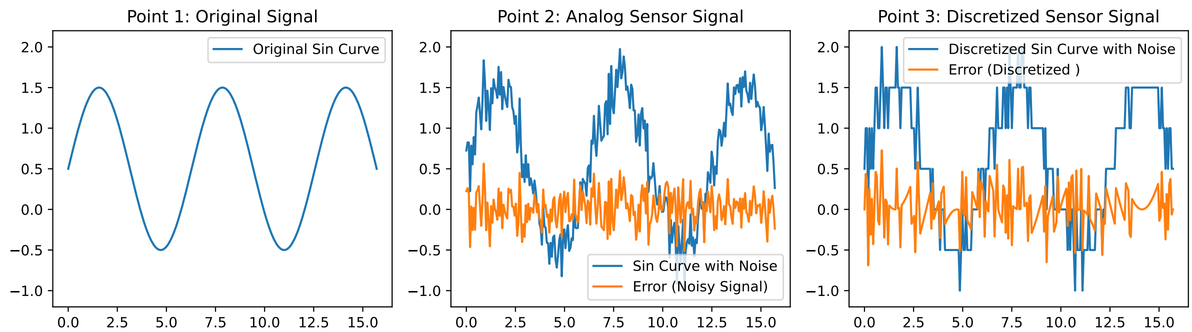
Validation: Black Box Testing. Results match expectations Verification: White Box Testing. Establish algorithm's truth

2.3 Signal Discretization

State values of the real system are never measured without some error. Upon measurement, sensor values are discretized by converting it to a digital signal. This happens in two steps that are presented in an exemplary setup in figure 2.5a. In the first step the real state value gets converted into a sensor signal by measuring it within a pitot tube. Within this step, some white noise generally occurs. Within the second step the sensor value gets converted to a digital signal by feeding it into an Analog Digital Converter (ADC). During the ADC step a discretization error occurs. Based upon sampling rate discretization errors occur in time and value direction. After the transformation by both steps, the data series contain a white noise sensor error as well as a discretization error (see figure 2.5b, Point 3). Great effort is made to avoid such errors. For sensor errors i.e. a nose boom is fitted to the aircraft to measure undisturbed stream conditions. For value and time discretization the resolution of the ADC is chosen to guarantee necessary parameter precision. An exemplary signal transforming process is shown in figure 2.5b.



(a) pitot tube setup for measuring dynamic pressure



(b) Original signal into measured and discretized signal

Figure 2.5: Simplified, exemplary signal processing flow for measurement of a dynamic pressure for real (1), analog sensor (2) and discretized sensor (3) values

The dynamic pressure in the air (denoted by 1) is ideally undisturbed and smooth for the actual state value. Within the sensor and stream close to the aircraft, the air is disturbed by the aircraft itself and also by the sensor, leading to the measured value at position 2. signal conversion from pressure to a voltage as well as discretization of the analog voltage to a digital signal is summarized within the ADC-Box since it is assumed that the errorwithin the pressure conversion is small compared to the errors within sensor and actual ADC. A sample signal conversion is shown within figure 2.5b. Of course, errors are exaggerated for illustration since state of the art systems possess a far smaller level of sensor as well as ADC error.

All recorded sensors are present in values that are already is a process that is integral to digitally recorded sensor values.

-mention data information -information loss through discretization

Time discretization value quantization

2.4 control systems approach

what are state values?

Following the recipe for a modeled aircraft based on sensor data we try to simulate the parameters x and u of the aircraft with the sensor data y. Khaled shows that this approach works for linking omega$_x omega_y, delta_d elta(driftangle) with omega_z .and Transmissibility function$T

The examined approaches include:

1. Transmissibility functions $\mathcal{T}$ that model the system output without having to take the unknown system input into consideration
2. Bond Graphs to model a physical rigid aircraft system
3. Physical relations
4. redundancies between sensors

model based fault detection(isermann) -parameter estimation (process modeling with linear or nonlinear functions, unknown process parameters are modeled by residual minimization) -parity equations () -state estimation (kalman), state/output observers (for known process parameters,) -principle component analysis

2.5 Sensor Errors+SignalProperties: A quick recap(See Engineers guide to Signal Processing)

Definition Fault Detection + Fault Diagnosis (Fault-Diagnosis Applications)

Signal properties are examined for a given signal in figure 2.6

Sensors generally produce errors within expected forms of output. -Noise -Measure using Covariance –> autocovariance -Offset -No response

Statistical representation of: Mean

[SMIT, S.13-17]

Time continuous mean

$$\mu = \frac{1}{T} \cdot \int\limits_{T} x(t)dt \tag{2.1}$$

Time discrete mean:

$$\mu = \frac{1}{N} \cdot \sum_{i=1}^{N} x_i \tag{2.2}$$

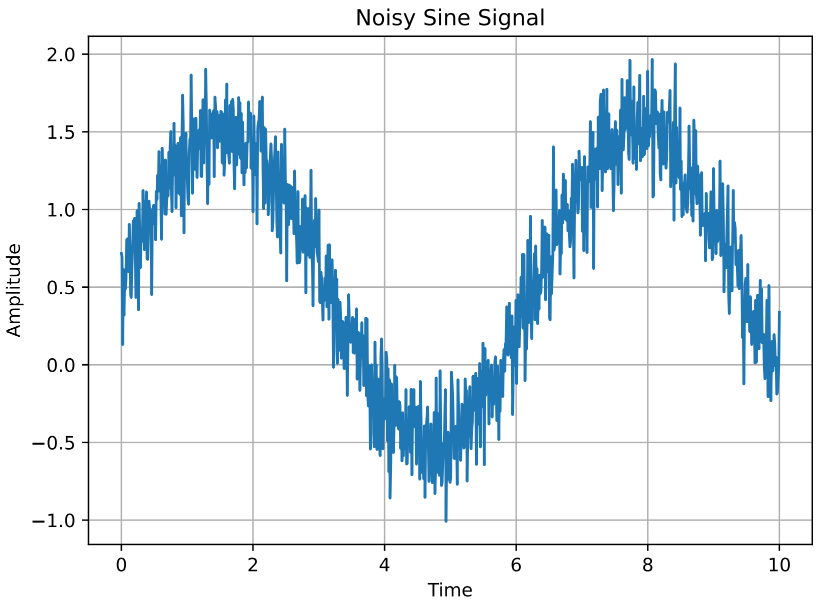


Figure 2.6: Noisy Sine Signal

The variance σ^2 is a metric for the signal's behaviour. It expresses the mean squared deviation from the mean.

Time

$$\sigma^2 = \frac{1}{T} \cdot \int_T [x(t) - \mu]^2 dt \tag{2.3}$$

$$\sigma^2 = \frac{1}{N} \cdot \sum_{i=0}^{N} [x_i - \mu]^2 \tag{2.4}$$

The standard deviation is derived from the variance. Its value gets square-rooted to better represent the power (magnitude of the amplitude).

Standard Deviation

$$\sigma = \sqrt{\sigma^2} \tag{2.5}$$

Mean and the standard deviation don't represent the desired metrics in some use cases. Rather more important is a comparison between the two. Hence, the Signal-to-Noise ratio (SNR) is used to compare and condense the mean and standard deviation by dividing the mean by the standard deviation.

$$SNR = \frac{\mu}{\sigma} \tag{2.6}$$

Another parameter is the coefficient of variation (CV) which is the standard deviation divided by the mean and multiplied by 100%.

$$CV = \frac{\sigma}{\mu} 100\% \tag{2.7}$$

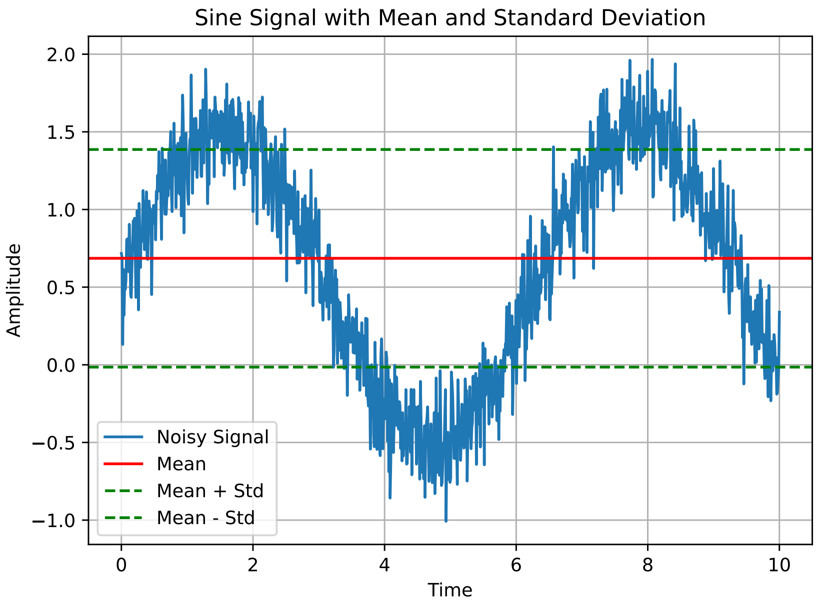


Figure 2.7: Sine Signal with mean and standard deviation

An arising problem based on the SNR and CV are however that they scale based on the mean value. Should the mean value lie at about 0 for e.g. a sensor of an aircraft control surface, the signal to noise ratio will be relatively high compared to an acceleration sensor in z axis with a constant offset of 1g

Practical example for mean and standard deviation in a given signal are overlayed in figure 2.7

To evaluate a signal according to the quantities the next logical step for statistic Histogram

probability mass function

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{2.8}$$

Covariance Zeitkontinuierliche Autokovarianzfunktion

$$\gamma(\tau) = \frac{1}{T} \cdot \int_T [x(t) - \mu] \cdot [x(t-\tau) - \mu] dt$$

Zeitdiskrete Autokovarianzfunktion

$$\gamma(k) = \frac{1}{N} \cdot \sum_N [x_i - \mu] \cdot [x_{i-k} - \mu]$$

–>Autocovariance autocov(x,x) = cov(x,x)

Correlation (Pearson coefficient)

$$\rho_{x,y} = corr(x,y) = \frac{cov(x,y)}{\sigma_x \sigma_y}$$

Total correlation 1 or negative correlation -1.

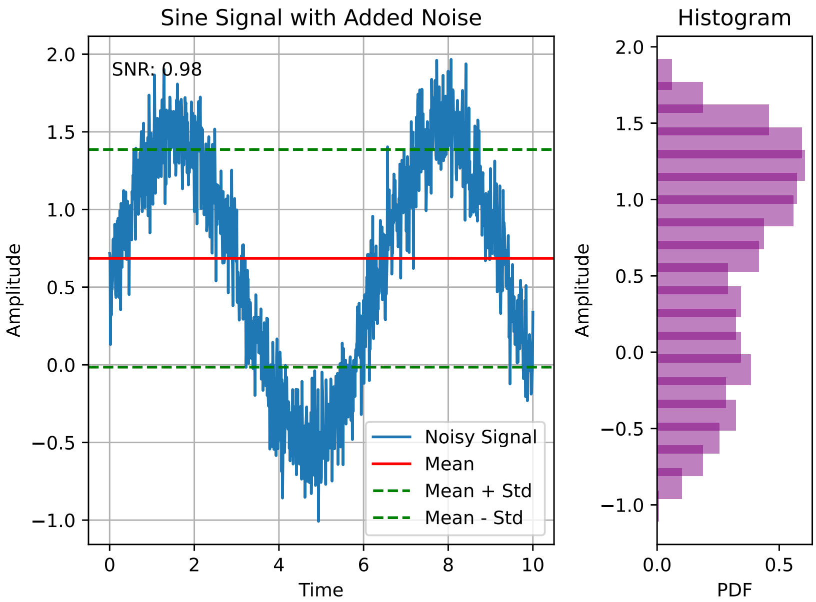


Figure 2.8: Sine Signal full analysis with mean, stdev, SNR and Histogram

Total independence for $\rho_{x,y} = 0$ not given since Pearson coefficient only detects linear correlations

Other correlation methods as rank-correlation (Spearman, Kendall) that detect change correlations are possible but are more complex in the implementation.

stft.

Test noise analysis over short time window of 256 samples.

Define here

Also, next to the simple and known models to display an error is the Luenberger Beobachter. enter placeholder for image: Measurement equals signal + error and image: luenberger beobachter. Kalman Implementierung (Lie13) Parameter Correlation Studies (Li15)

2.6 Faults

Offset, bias, hysteresis from literature

Fault definition from [fmea? Isermann(20)] primary and secondary data ([GIEZ22])

2.7 Intro existing architectures

Sensor data is presently already generated and uploaded to the skystash architecture described in chapter 2.9 while it is uploaded

2.8 DAQs, ISTAR

DLR data generation (DAQs) (How Data is checked)

Matthews flowchart(dataflow from sensor voltage through computer-computer-user) Exemplary for a single sensor.

The ISTARs DAQ records the aircrafts own flight data bus (ASCB, avionics standard communications bus), the experimental Noseboom, an additional GPS unit and various additional strain gauges and acceleration sensors that are distributed across the aircraft. configuration currently is described differently within each sub-group.

2.9 skystash

dlrk paper hier zitieren.

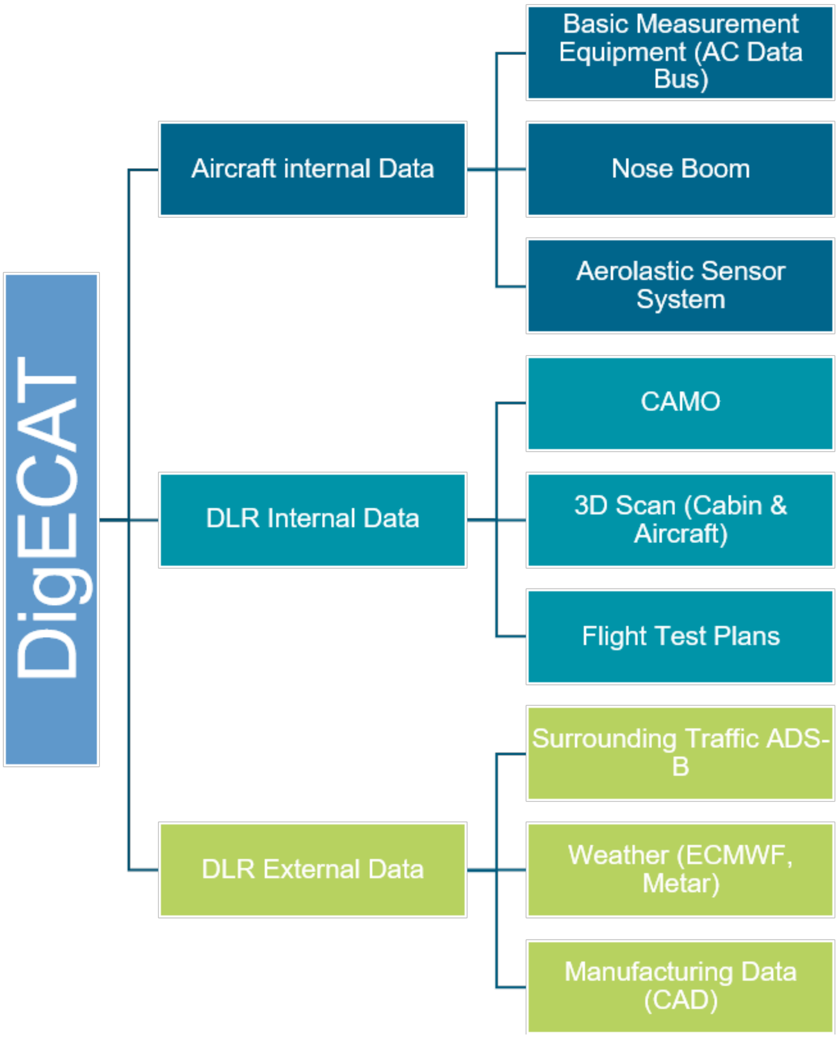


Figure 2.9: Generation of flight test data

the skystash is a platform to distribute, analyze and visualize large flight data sets. It is currently in development within the DLR's digital twin project and aims to be a service platform for uploading and sharing the DLR's flight test data. Various requirements are posed from different sources such as flight guidance projects that are content with sampling rates as 1 Hz and aeroelastic examinations that receive sampling rates of 2000Hz. For this purpose a dynamic data export is sensible in which users can directly choose sampling rates as well as single parameters from a flight contrary to downloading and working with a whole flight data set averaging up to 2GB of data.

This work builds upon the python api and tries to implement and test an algorithm that checks the data for the istar aircraft

2.10 downloadfunctionalities

file sizes too large –> Reduction for on demand parameters and resampling utility Handling of large data sets

2.11 Deep dive into altitudes

The aircraft altitude generally is defined as the displacement of the aircraft from sea level. On a geodetic scale, the earth can be described as an ellipsoid due to its rotation. However, varying density levels of the earth's crust cause the elevation and sea level to deviate from the ellipsoid shape. This results in a lopsided model that is modeled in the WGS84 (ref and image here) system. This is also the altitude that the gps measures. And will be the reference altitude for the following calculations.

The main existing altitudes are the:

1. Geodetic Altitude (GNSS)
2. Barometric Altitude (used in conjunction with reference pressure)
3. Inertial Altitude
4. Radar Altitude (can be used in conjunction with a terrain model to derive geodetic altitude)

Possible errors for each are: geodetic: inconvenient satellite placements, deflection of signals in the atmosphere and signal problems Barometric Altitude: Possible errors due to drift and meteorological atmospherical pressure shifts, Reference Altitude.

Going into WGS84 and the GNSS Altitude however exceeds the scope of this work. In the following, the satellite altitude above Mean Sea Level (MSL) is considered as the reference altitude.

2.12 gnss algorithms

Fault detection algorithms within GNSS are described as Receiver Autonomous Integrity Monitoring (RAIM) are tried and tested within GNSS implementations since high accuracy positioning is valuable for various applications, reaching precisions of up to a few centimeters. Explaining the full function of position calculation exceeds this works' scope. To summarize however, GNSS inputs form an overdefined system of equations which needs to be compensated within some algorithm to form one position based on multiple inputs.

ica18 annex10 ABAS, RAIM, AAIM

3 Problem Statement

- prototype for a complex sensor health monitoring structure. -employing standardized data classes -metadata semantics (SOIL) -pandas series -employing standardized interfaces for modular expansions

-structuring

4 Methods

4.1 Noise approximation via STFT

Limits of variance and stdev.

To better approximate the errors concerning white noise, a STFT is employed.

White noise approximation methods. Rolling window variance.

4.1.1 Intro Fourier and Short time Fourier Transformation

4.1.2 State of the art

TODO: Comparison variance, standard deviation, mean noise. Scalability for other sensors.

Noise Tracking using DFT can be used to estimate noise combined with a strenuous effort [HEND08].

Since this however would exceed the scope of this work, a simpler algorithm is implemented by comparing moving window variance as well as STFT overall amplitude estimations.

4.2 altitude comparison

some mean ground has to be found to crossreference the various altitudes.

For standardization. The SI-unit meters is used for altitudes.

In the first draft. The altitude is sampled with 1Hz for computational speed and since gnss update rates are updated in a similar frequency.

4.2.1 The barometric altitude based off of the International Standard Atmosphere (ISA) [ISO75]

The international standard atmosphere is the conventional method of measuring the aircraft altitude based off of air pressure. The method can be understood as a function of pressure and reference pressure (differing based on weather) that returns an altitude. In the following this equation based on fundamental scientific correlations will be derived.

In the beginning a finitesimally small element of the atmosphere is considered that is in equilibrium. It has pressure acting upon it from all its sides. The pressure acting upon all its sides generate a force that cancels out within the horizontal directions. It is notable however that the pressure on the top marginally differs from the pressure on the bottom. This arises from the elements desire to remain in stationary as it is attracted by gravity. Were the pressure difference on top and bottom equal, the element would begin moving towards the origin of the gravity vector.

Since we are interested in the difference in pressure we formulate the force equilibrium for direction h in equation 4.1. Please note that the original gravity term of course is $\rho \cdot dV \cdot g$ but we transform it using the correlation $dV = dA * dh$ with dA being the area of the elements top and bottom side.

From equation 4.1 follows 4.2. Using the perfect gas formula $p = \rho RT$, ρ can be taken out of the equation and equation 4.3 emerges.

At this point we need to introduce the Temperature model of the ISA. It assumes linear temperature gradients for each layer of the atmosphere, meaning that each atmospheric layer can be modeled using a single coefficient that models the gradient. In the following, this gradient will be used as $a = dT/dh$. This allows modeling the temperature for each atmospheric layer with equation 4.4.

Using the different coefficients from table 4.1 we now can model the Temperature based on a standard temperature of 15° Celsius or 288.15Kelvin at Mean Sea Level (MSL), meaning that $h = 0$. The temperature gradients drastically simplify real circumstances but work as an empirical estimate that is good enough to guarantee a common understanding of barometric altitudes. This is especially important for aeronautic applications since altitudes for directing flights are generally given in barometric altitudes.

Now, substituting the ISA-equation 4.4 into 4.3 delivers 4.5. To get this partial differential equation into a regular formula we need to integrate which resolves into equation 4.6. The borders chosen for integration are the lower border of the atmospheric layer referenced with the index 0 and the other layer being the running variable.

Substitution of the single factors follows in equations 4.2.1. Subequation c is then simplified by pulling T_0 into the denominator and the ISA-equation 4.4 is substituted.

After substituting, the term 4.7 emerges. Brief transformation then resolves into 4.2.1. Resubstituting then gives equation 4.9

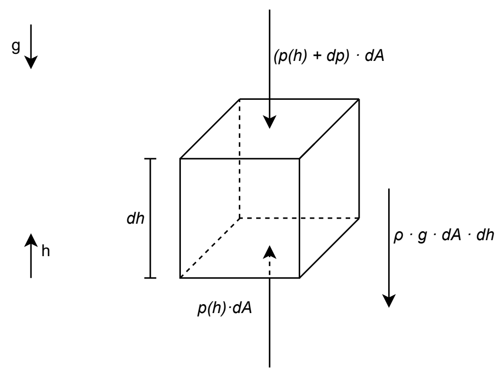


Figure 4.1: Forces around a finitesimally small element

quick derivation of barometric formula based on the pressure pde.

Resulting from the equilibrium around a finitesimally small element in figure 4.1.

follows the force equilibrium for force terms as well as the gravity term

$$\sum F_h = 0 = p(h) \cdot dA - (p(h) + dp) \cdot dA - \rho \cdot g \cdot dh \cdot dA \tag{4.1}$$

resolves into:

$$dp = -\rho \cdot g \cdot dh \tag{4.2}$$

with ideal gas formula

$$\frac{dp}{p} = \frac{-g}{R \cdot T} \cdot dh \tag{4.3}$$

and T = f(h) from Interational Standard Atmosphere ISA-correlation

$$T(h) = a \cdot h + T_0 \tag{4.4}$$

with a being defined as dT/dh and -6.5 K/km for the troposphere. See Table 4.1 Since Temperature behaviour is defined by the ISO [ISO75] within the ISA as follows: perhaps mention troposphere, strato, pause,... here

Atmospheric Layer	Geopotential Altitude [km]	Temperature T at bottom [K]	Temperature gradient a [K/km]
Troposphere	-2-0	301.15	-6.5
Troposphere	0-11	288.15	-6.5
Tropopause	11-20	216.65	0
Stratosphere	20-32	216.65	1
Stratosphere	32-47	228.65	2.8
Stratopause	47-51	270.65	0
Mesosphere	51-71	270.65	-2.8
Mesosphere	71-80	214.65	-2

Table 4.1: International Standard Atmosphere cite ISO75

$$\frac{dp}{p} = \frac{-g}{R * (a * h + T_0)} * dh \tag{4.5}$$

integrating with borders 0 and the running variable resolves in:

$$\ln(\frac{p}{p_0}) = -\frac{g}{a \cdot R} \cdot ln(\frac{a * h + T_0}{a * h_0 + T_0}) \tag{4.6}$$

substituting single terms for easier calculations resolves in:

$a = p/p_0$
$b = \frac{-g}{a \cdot R}$
$c = \frac{a*h+T_0}{a*h_0+T_0} = 1 + \frac{a\cdot(h-h_0)}{a*h_0+T_0} = 1 + \frac{a\cdot(h-h_0)}{T(h_0)}$

and substituting $a \cdot h_0 + T_0 = T(h_0)$ within the last step in c collapses the equation 4.6 into:

$$\ln(a) = b * \ln(c) = \ln(c^b) \tag{4.7}$$

taking the exponent of the equation follows to:

$$\rightarrow a = c^b$$

(4.8)

and with resubstitution the barometric pressure formula for a temperature coefficient that is not zero results:

$$\frac{p}{p_0} = \left(1 + \frac{a \cdot (h - h_0)}{T\,(h_0)}\right)^{\frac{-g}{a \cdot R}} \tag{4.9}$$

p	= pressure at current altitude [Pa]
p_0	= reference pressure [Pa]
h	= current altitude [m]
h_0	= reference altitude [m]
$T(h_0)$	= temperature at reference altitude[K]
a	= ISA Temperature Coefficient depending on altitude (-6.5e-3)[K/m]
g	= gravity constant (9.80665) [m/s^2]
R	= Ideal Gas Constant (287.05287)[m$^2/(K \cdot s^2)$]

This formula however is not valid for a being equal to 0. So the barometric pde 4.5 needs to adapted to $a = 0$ before integration.

$$dp/p = -g/(R * T_0) * dh$$

$$ln(p/p_0) = -g/(R * T_0) * h$$

This results into the barometric equation for constant temperature coefficient as

$$\frac{p}{p_0} = exp\left(\frac{-g}{RT(h_0)} \cdot (h - h_o)\right) \tag{4.10}$$

resolving into a function of h

$$ln(\frac{p}{p_0}) = \frac{-g}{RT(h_0)} \cdot (h - h_o)$$

$$h = ln(\frac{p}{p_0}) \cdot \frac{RT(h_0)}{-g} + h_0 \tag{4.11}$$

Now, using equation 4.9 for $a \neq 0$ to calculate altitude as a function of pressure:

$$1 + \frac{a}{T(h_0)} \cdot (h - h_0) = \left(\frac{p}{p_0}\right)^{\frac{1}{\frac{-g}{a \cdot R}}}$$

$$\rightarrow h = \left(\frac{p}{p_0}^{\frac{-a*R}{g}} - 1\right)\frac{T(h_0)}{a} + h_0 \tag{4.12}$$

Formula 4.12 is the equation used for ISA-assumptions within a atmospheric layer with temperature change.

in aerospace context this gets used as follows.

p_0 is the reference pressure which gets used in conjunction with T_0.

Based upon reference pressure, the pressure value in at the boundary levels can be estimated.

If altitude gets calculated, it needs to follow in two steps. Based on ideal temperature at sea level

1. determine which ISA-Level is present by determining p/p$_0 at the boundaries.$p/p$_0 = f(h)$)

2. base calculation off of isa reference level p/p

$$(a * h/T_0 + 1)/(a * h_0/T(h_0 + 1)$$

TODO: implement g as a function of lat and long

For further use, the barometric formula will be expressed as

$$h = f(p, p_0)$$

in accordance to ISO75 the altitude is the geopotential altitude which is equivalent to the orthometric height and MSL.

Also available is the geometric altitude which references the earth ellipsoid as its base and which is generally used by geodetic applications as a geometrically reliable reference system.

4.3 Finding a reference state

Goal of this work is finding a reference frame for all parameters into which they can be transformed into and back.

A starting point which shall be considered is the geodetic reference.

it measures the aircraft's position by its displacement from the previously (ref?) discussed WGS84 system.

Meaning that altitude gets measured as the orthometric height (see ellipsoid height-geoid height).

Latitude and Longitude form the x and y axis of the COS. True heading forms the reference heading within the geodetic system.

All aircraft parameters related to motion and position of the aircraft should be attempted to be condensed into this form.

4.4 error detection and mitigation

Examination of Receiver autonomous integrity monitoring (RAIM) from GNSS applications.

basic principle 1 in 1 out basic

2 in 1 out mean solution. Detect discrepancies 1. simple solution: take average 2. detect discrepancies but still take average

3+ in 1 out. 1. take average 2. detect value with strong variations and isolate (it is assumed that only 1 sensor is faulty) 2.1 predict value and deny value if it is larger than 3 times standard deviation (Wen07, 239).

implementation details. see [Bro92]

5 Implementation

5.1 Software architecture considerations

Careful consideration needs to be given to the workflow of the level 1 check to allow scalability and minimal manual interaction in later stages. To achieve this architecture, manual steps are reduced as far as possible. However, some level of configuration must be implemented. Otherwise only relational sensor behaviour could be detected. Meaning that sensor faults occuring temporarily within an experiment can be detected but permanent behaviour is not noticed by a relative algorithm

5.2 Level 1 Implementation

For implementing the level 1 checks, the measured data needs to be compared to the expected data. To gain insight into what the the expected data is, the configuration file of the data acquisitioning system needs to get parsed. Luckily, the DAQ's format is a .zip directory. The 7zip command line tool gets used for opening the configuration file since the configuration file's format is not fully complying to the zip standard making several python libraries fail during the process. This stems from an issue with the zip header and footer parts of the file that are not at expected places (i.e. the front the back). Once opened, the configuration file contains multiple files as well as an essential xml file that contains the needed sensor metadata.

Missing datasets can now easily be found by comparing the expected values from the configuration file to the actual generated data.

For the second step.

5.3 Level 2 Implementation

Since the IMC DAQ System resamples the 20Hz Sensors to a straight timeframe data gets lost in the process. This makes potentially noisy sensors output the same value twice in a row since the DAQ hasn't yet received the new sensor data and outputs the same value multiple times in a row. Even sensors with a high noise ratio such as the fine part of a gps latitude signal outputs the same value twice in a row which is highly unlikely to happen on a statistical basis. Since this occurs quite often the question arises if the actual sampling may be lower than the actual data.

5.4 Level 3 Implementation

Aims of Level 3 Implementation are to model the aircraft's state in a reference system. This reference system shall be geodetic and fixed to the earth while the aircraft moves through it. Moving aircraft coordinate systems like the aerodynamic and the along track Coordinate system may be derived from its geodetic position using ?angles and velocities.

Interfacing: Clean interfaces are generated throughout the model. Enabling a standardized state vector x. Meaning that A remains standardized for any aircraft while B, U and L need to be adjusted for any changes to the aircraft or sensor data.

The integration step may be omitted in early design stages since the necessary equations and equilibriums of Forces and Moments could only be modelled linearly while neglecting various unknown factors like shifting CG due to fuel burn, actual Inertia of Aircraft and aicraft mass. Hence, this step may be implemented if time allows it.

5.5 Examining Altitude Sensors

As seen in 5.1 gps altitudes have a base mean value of difference of about 3-4 meters. During flight level changes the base level changes significantly. Further investigation is needed how these changes may arise.

One possible approach would be considering different placements of gps antennas within the airframe. since the IMAR's position is precisely known and lies around the center of gravity but the ASCB's gps position is not known exactly the process is not facilitated. However using the process of lever arms the position could be roughly estimated and compensated from the altitude difference in figure 5.1.

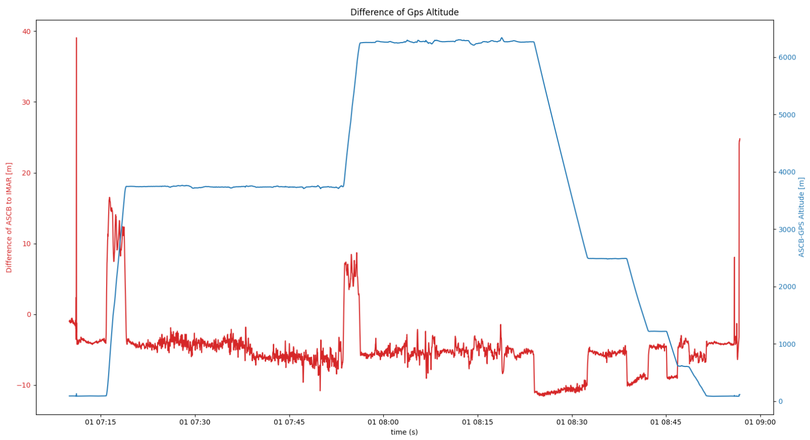


Figure 5.1: GPS difference for the aircraft base platform (ASCB) as well as experimental sensor (IMAR)

Another incurring deviation is investigating the 40m/150ft offset for gps altitudes. Possible causes may be Uncorrected Ellipsoid gnss altitudes. However, this appears unlikely since generally the offset in the region would be added and not subtracted [further investigation needed].

Difficulty diagnosing sensors without previous knowledge. limitations within sensor behaviour. Checks include: range, too much sensor movement, too few sensor movement.

Relative examinations possible for errors occuring for finite time within experiment but not if all of the experiment data is corrupt.

6 Results

7 Conclusion

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