Name:

Matr.-Nr.:

Thema:

Betreue

Aachen, den

Diese Arbeit wurde vorgelegt am Werkzeugmaschinenlabor WZL,
Lehrstuhl für

Aachen, 26. March 2023
V. Name - Tel. 0241-80 xxxxx

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

III List of Figures

IV List of Tables

1 Introduction

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).

1.1 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.

1.2 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.

1.3 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`

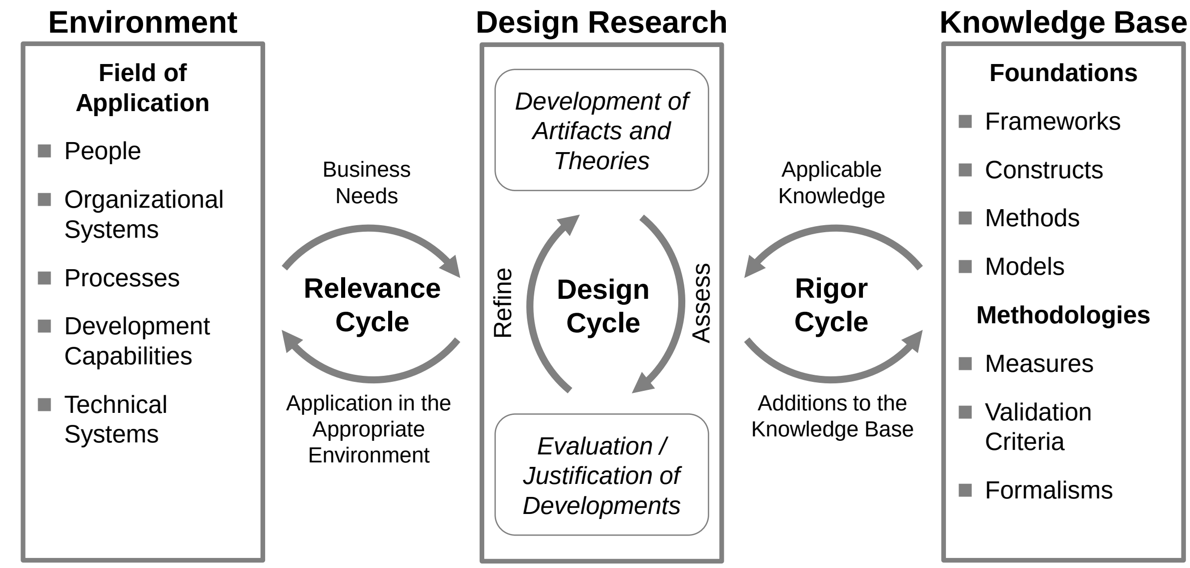

Figure 1.1: TMP: Design science research framework original image [**HEVN04**].

1.4 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				

1.5 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`

1.6 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 Theoretical Background

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.

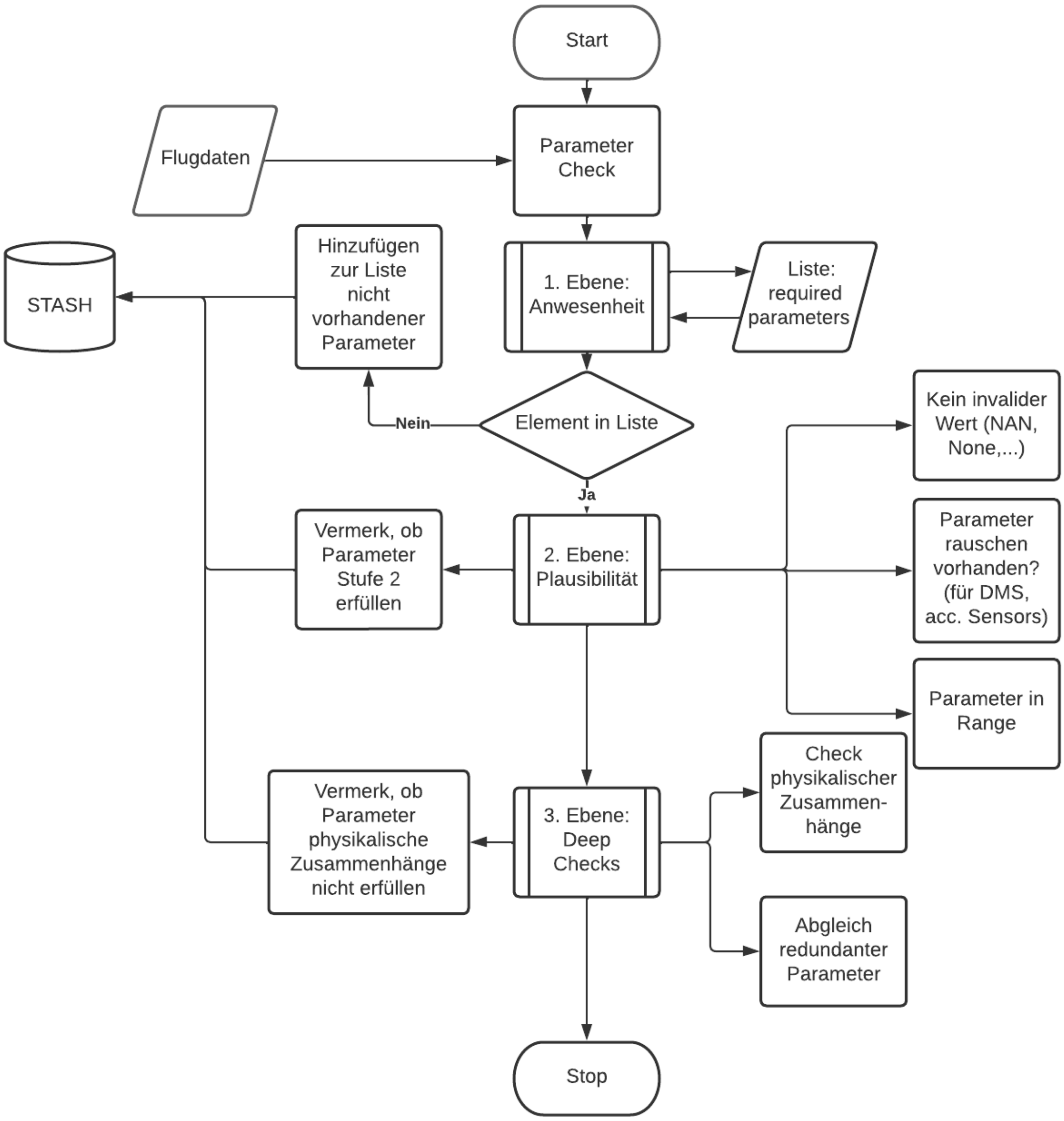

Figure 2.1

2.1 Sensor Errors: A quick recap(See Engineers guide to Signal Processing)

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

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

Statistical representation of: Mean

[SMIT06, S.13-17]

Time continuous mean

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

Time discrete mean:

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

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.

$$SNR = \frac{\mu}{\sigma^2} \tag{2.6}$$

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

$$CV = \frac{\sigma^2}{\mu} 100\% \tag{2.7}$$

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 noise, sinus wave, superposed sinus wave

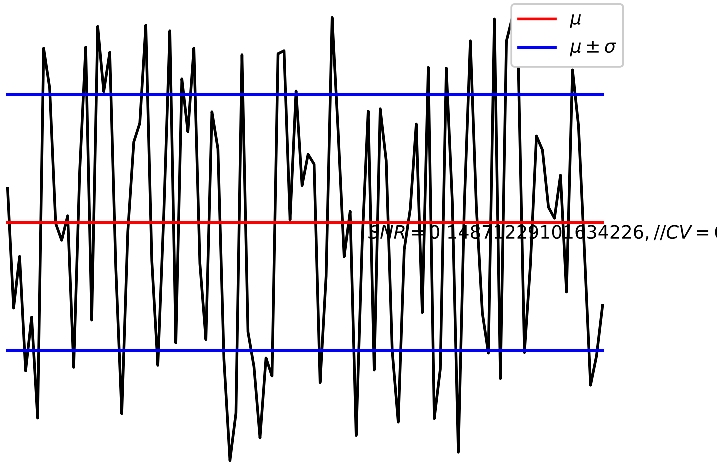

Figure 2.2: Mean and standard deviation for a white noise signal

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

probability mass function

Covariance –>Autocovariance

Correlation

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)

2.2 Integrity, Reliability and Validity based on GNSS

Data according to ISO 8000 cite [ISO22] iso5725: -accuracy(validity)+precision(reliability) Also see precision and accuracy definition [SMIT06, S.33ff.]

cite faa08 B.1.5: Reliability = 1-Probability$_{F}ailure$

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 control systems approach

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$_{x}omega_{y}, delta_{d}elta(driftangle)withomega_{z}.andTransmissibilityfunction$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

2.4 Intro existing architectures

2.5 Data Format, FAIR

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

2.6 Faults

Fault definition from [Isermann(20)][HALO-Report]

2.7 Stash

2.8 downloadfunctionalities

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

2.9 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.

2.10 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

2.11 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.

2.12 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.

2.13 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.

2.14 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.

3 Problem Statement

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.

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

Noise Tracking using DFT cite [Hen08]

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.

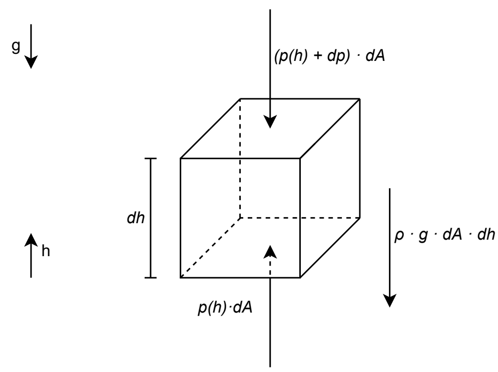

Figure 4.1: Forces around a finitesimally small element

quick derivation of barometric formula based on the pressure pde.

$$p = p_0 \cdot \left(1 + \frac{a \cdot (h - h_0)}{T\,(h_0)}\right)^{\frac{-g}{a \cdot R}} \tag{4.1}$$

p = pressure at current altitude
p_0 = reference pressure
h = current altitude
h_0 = reference altitude
a = ISA Temperature Coefficient depending on altitude
R = 287Ideal Gas Constant

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

with for the volume:

$$dV = dA * dh$$

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

$$m \cdot g$$

$$0 = \rho \cdot g \cdot dA \cdot dh + (p(h) - dp) \cdot dA - p(h) \cdot dA$$

–> dp=-$\rho \cdot g \cdot dh$(4.2)

with ideal gas formula

$$p = ro * R * T$$

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

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

$$T = a * h + T_0$$

with a being defined as dT/dh and -6.5 K/km for the troposphere.

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

integrating resolves in:

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

substituting:

$a =$ p/p_0

$b =$ -g/a*R

$c =$ (a*h+T_0)$/(a * h_0 + T_0) = 1 + (h - h_0) * a/(a * h_0 + T_0)$

with

$$T(h_0) = a * h_0 + T_0$$

–>

$$c = 1 + (h - h_0) * a/T(h_0)$$

resolves in

$$ln(a) = b * ln(c) = ln(c^b) - - > a = c^b$$

Geopotential Altitude [km]	Temperature T [K]	Temperature gradient a [K/km]
-2-0	301.15	-6.5
0-11	288.15	-6.5
11-20	216.65	0
20-32	216.65	1
32-47	228.65	2.8
47-51	270.65	0
51-71	270.65	-2.8
71-80	214.65	-2

Table 4.1: International Standard Atmosphere cite ISO75

$$\frac{p}{p_0} = (1 + \frac{a}{T(h_0)} * (h - h_0))^{\frac{-g}{a*R}} \tag{4.3}$$

Also consider term for a=0

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

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

solve towards c

$$c = a^(b^-1)$$

Resubstituting

$$1 + (h - h_0) * a/(T(h_0)) = (p/p_0)^(1/(-g/(a * R))$$
$$h = (\frac{p}{p_0}^{\frac{-a*R}{g}} - 1) * T(h_0)/a + h_0 \tag{4.4}$$

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.

Since Temperature is defined as follows:

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

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

TODO: implement g as a function of lat and long

For further use, the barometric formula will be expressed as

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

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.

5 Implementation

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.

5.1 Examining Height and altitude

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.

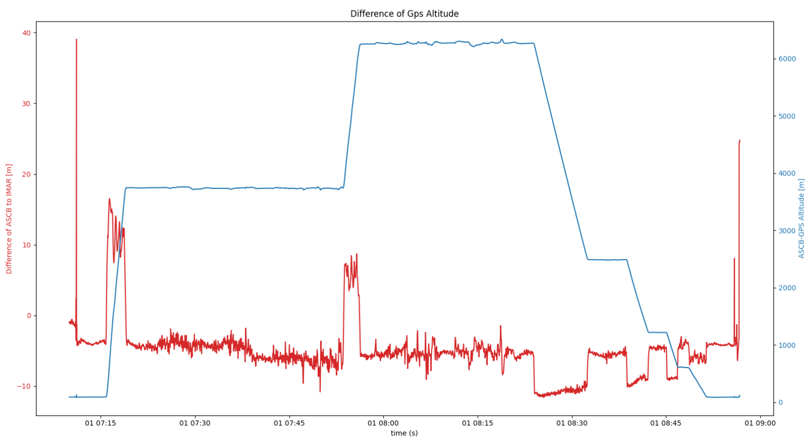

Figure 5.1: GPS difference for the aircraft base platform (ASCB) as well as experimental sensor (IMAR)

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].

6 Results

7 Discussion

8 Conclusion

References

[BODE21] M. Bodenbenner, M. P. Sanders, B. Montavon, and R. H. Schmitt. "Domain-Specific Language for Sensors in the Internet of Production". In: *Production at the leading edge of technology*. Ed. by B.-A. Behrens, A. Brosius, W. Hintze, S. Ihlenfeldt, and J. P. Wulfsberg. Lecture Notes in Production Engineering. Berlin, Heidelberg: Springer Berlin Heidelberg, 2021, pp. 448–456. ISBN: 978-3-662-62137-0. DOI: \url{10.1007/978-3-662-62138-7{\textunderscore}45}.

[SMIT06] S. W. Smith. "Digital Signal Processing". In: *Digital Signal Processing*. Elsevier, 2006, p. i. ISBN: 9781904275268. DOI: \url{10.1016/B978-1-904275-26-8.50019-1}.