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Bachelor's Thesis

Large Eddy Simulation of Heat Transfer on Wing surfaces in 3D

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Declaration of Academic Honesty

I hereby affirm in lieu of an oath that the present bachelor's thesis entitled

"Large Eddy Simulation of Heat Transfer on Wing Surfaces in 3D"

has been written by myself without the use of any other resources than those indicated, quoted and referenced.

Graz, 16 March 2015

Stefan LENGAUER,

Preface

This thesis was written as part of my bachelor's degree program at FH Joanneum, University of Science in Graz, Austria.

One of the challenges in the conduction of this project was the location of the necessary hardware, which was at the department's facility. This required a physical attendance at the university for the majority of the work. Also the literature research proved difficult, since there is not yet that much material covering this specific topic.

With regard to this obstacles I am satisfied with the outcome of this project and I hope to provide the reader with a broad overview on the basics of Large Eddy Simulation as well as its advantages and disadvantages.

Thus I want to thank everyone who supported me writing this thesis.

Contents

Abstract

Large Eddy Simulation, a subdomain of Computational Fluid Dynamics, is recently experiencing an increased attention, due to increasing capabilities of the necessary hardware, in detail CPU and memory. In most sectors it is not yet industrial standard, because of its height demand in terms of resources, but it will most likely become an important tool for the investigation of complex flow problems in near future.

Therefore this bachleor's project compromises the execution of a high-resolution simulation of the heat transfer on a wing surface in three dimensions. The given geometry for this task is a NACA 0012 airfoil and the used software tools are Ansys ICEM and Ansys CFX.

Subsequent the achieved results are compared to results obtained from a similar RANS simulation, which is nowadays standard for industrial application. Based on this evaluation the applicability of LES is scrutinized and discussed.

Kurzfassung

Large Eddy Simulation, ein Teilbereich der numerischen Strömungsmechanik, erfährt in letzter Zeit erhöhte Beachtung dank der steigendenden Leistungsfähigkeit der erforderlichen Hardware, insbesondere CPU und Speicher. In den meisten Bereichen ist sie aufgrund ihres hohen Ressourcenaufwandes noch nicht Industriestandard, aber in naher Zukunft wird sie ein wichtiges Instrument zur Untersuchung von komplexen Strömungsproblemen werden.

Aus diesem Grund beinhaltet dieses Bachelorprojekt die Durchführung einer hochauflösenden Simulation eines Wärmeübergangs an einem dreidimensionalen Flügelprofil. Die für diese Aufgabe gegebene Geometrie ist ein NACA 0012 Flügelprofil und die verwendeten Softwarepakete beinhalten Ansys ICEM und Ansys CFX.

Anschließend werden die erzielten Resultate mit den Resultaten einer vergleichbaren RANS Simulation verglichen, welche momentan Standard für industrielle Anwendufngen sind. Diese Auswertung dient als Grundlage für die darauffolgende Untersuchung und Diskussion der Anwendbarkeit der Large Eddy Simulation.

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List of Symbols

c_p	Specific heat coefficient, J/kg K
k	Turbulent kinetic energy, m^2/s^2
ε	Turbulent energy dissipation rate, m^2/s^3
ϑ	Velocity scale, m/s
l	Length scale, m
ρ	Density, kg/m^3
μ_{SGS}	Dynamic sub grid scale viscosity, kg/m s
μ_t	Turbulent viscosity, kg/m s
ν	Kinematic viscosity, m^2/s
ν_t	Turbulent kinematic viscosity, m^2/s
λ	Heat conductivity, W/K m
Nu	Nußelt number, dimensionless
Re	Reynolds number, dimensionless
Pr	Prandtl number, dimensionless
Fr	Froude number, dimensionless
C_D	Drag coefficient, dimensionless
$F_{horizontal}$	Force in horizontal direction, kg m/s^2
σ	Stefan-Boltzmann constant, W/ m^2 K^4
τ_{ii}	Normal stresses, N/m^2
δ_{ij}	Kronecker symbol, dimensionless
Δ	Cutoff width, m
Q	Heat, J
h_c, α	Heat transfer coefficient, W/m^2 K
T_0	External boundary temperature, K
T_w	Walltemperature, K
q_w	Heat flux at wall boundary, W
q_{cond}	Heat flux caused by convection, W
q_{rad}	Heat flux caused by radiation, W
v	Characteristic velocity, m/s

η	Dynamic viscosity, kg/m s
y^+	Dimensionless wall distance, dimensionless
u_τ	Frictional velocity, m/s
τ_w	Wall shear stress, N/m^2
U	Mean flow velocity, m/s
Δy_1	First cell height, m
A_{eff}	Area facing in flow direction, m^2
Δt	Temperature difference, K
R_{LE}	Airfoil nose radius, m
t	Maximum profile height, m

List of Tables

List of Abbreviations

CAD	Computer Aided Design
CDS	Central Difference Scheme
CFD	Computational Fluid Dynamics
DES	Detached Eddy Simulation
DNS	Direct Numerical Simulation
GS	Grid Scale
GUI	Graphical User Interface
HPC	High Performance Computing
HPCC	High Performance Computing Cluster
LES	Large Eddy Simulation
RANS	Reynolds-averaged Navier Stokes
SGS	Sub Grid Scale
SST	Shear-Stress Transport
VLES	Very Large Eddy Simulation

Chapter 1

Introduction

The academic discipline of CFD (Computational Fluid Dynamics) emerged in the 1970s as alternative to the experimental and the theoretical approach for the prediction of flows. It relies on the physical modeling of a flow as mathematical problem which is then solved numerical. Nevertheless compared to other computer aided engineering domains it lagged behind for a long time due to the tremendous complexity of the underlying models for the description of fluid flows, which should be at the same time economical and physical sufficient correct. Although it comes with huge hardware costs, especially for the LES (Large Eddy Simulation), it is usually still more economical than an experimental facility and features various advantages like the capability of the investigation of very large systems, or systems under hazardous conditions [1].

The LES is a subdomain of the CFD and features dedicated filters which reject the smaller eddies and let the larger ones pass. This is done prior to the computation, where the smaller eddies are represented by turbulence models. The LES is usually more effort to implement and wrong choices of the models often lead to strong deviations of the results.

The analysis and prediction of turbulent flows is a critical factor for the comprehension of natural and technical flow processes. This basis is necessary for the improvement of objects surrounded by a flow like aircraft.

This chapter starts off with the basics of turbulent flows before it covers the technical principles of LES and heat transfer.

1.1 Basics of turbulent flows

Turbulences appear in a great range of shapes and sizes. Independent of their complexity, all flows become unstable above a certain Reynolds number. While they are usually laminar at low Reynolds numbers they become more and more turbulent, when it increases [2]. This specific value at which the flow turns over from laminar to chaotic is called critical Reynolds number [1].

Turbulences have always three-dimensional, spacial character, even if the velocities and pressures vary just in one or two dimensions. The typical signs of turbulence are the so-called turbulent eddies which are basically rotational flow structures as they can be seen in figure 1.1. The eddies come with a wide range of various length- and time scales and due to their rotational flow fields, particles which are initially separated by long distances can be brought together quickly, which leads to a high efficiency in terms of heat, mass and momentum exchange [1].

Although turbulent flows are highly chaotic and almost impossible to predict over longer periods of time, the characteristic lengths of the large eddies are proportional to the considered flow problem. An important term which has to be considered in this context is the energy cascade, which is widely known as Kolmogorov's energy cascade, named after the Russian scientist, who described these circumstances as first. In a typical turbulent flow kinetic energy is handed down from the large scale eddies, which are by far the most energetic ones, to the smaller ones. Figure 1.2 shows the spectral energy of eddies dependent on their wavenumber. The wavenumber is given by $\kappa = 2\pi/\lambda$, with λ as the wavelength of the eddies. Obviously the smaller eddies hold by far the least energy. The larger scales get their energy from the mean flow and break up in the smaller scales. The Reynolds number of the smaller scales equals one, which means that the inertia and the viscous effects are of equal strength. All the work they perform is against the viscous stresses and accordingly all the energy they hold dissipates into internal thermal energy [1, 2].

1.2 CFD attempts to deal with turbulence

In CFD there are different ways in order to deal with turbulent flows. All natural flows are more or less turbulent, but in the computation the turbulences are usually resolved

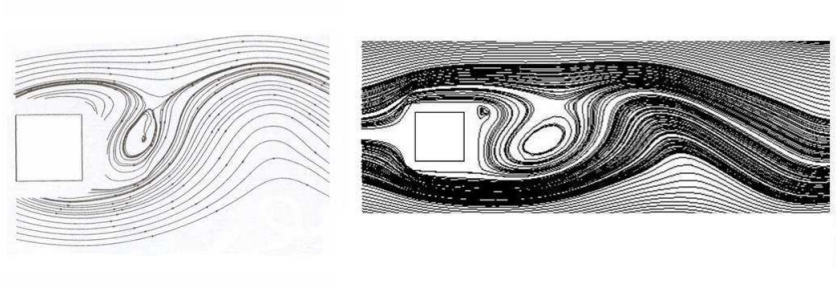

Figure 1.1: [5, p.13] Experimental and numerical streamlines

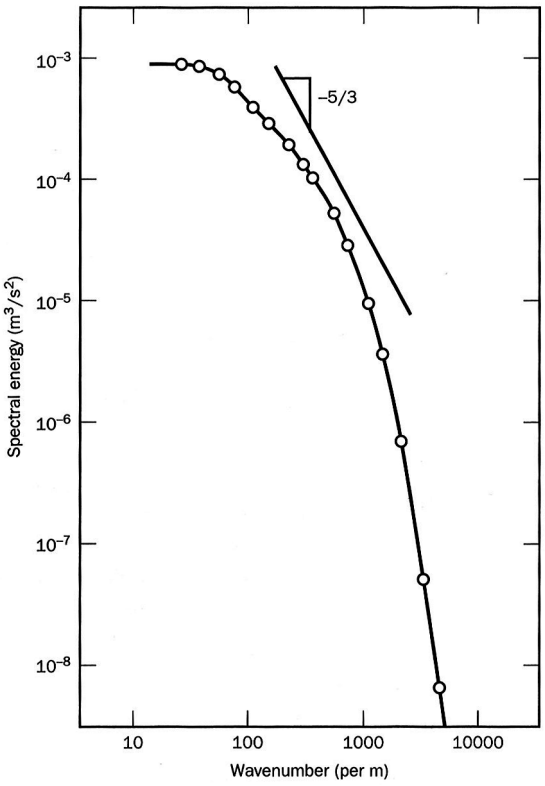

Figure 1.2: [1, p.43] Energy spectrum of turbulence of different scales

only to a certain degree or omitted altogether. Methods for calculation of flows can be organized according to their turbulence resolving capability.

The so called RANS (Reynolds Averaged Navier-Stokes) equations are the most common and wide-spread approach in order to deal with any flow prediction. This method yields time averaged properties of the flow like mean velocities, mean pressures, mean stresses, etc. For many technical flow investigations this is satisfying and therefore this simulation type has been the method of choice for CFD calculations for the past decades. Other advantages are the modest demand on resources and the fact that two-dimensional calculations are sufficient. The RANS equations for incompressible flows lead to six additional stresses, known as the Reynolds stresses. This

stresses are unknown and for computing turbulent flows they need to be predicted by dedicated turbulence models like the $k - \varepsilon$ model.

With DNS (Direct Numerical Simulation) all scales of turbulence are simulated numerical. Therefore a three-dimensional grid is needed, which is at least as fine as the smallest scale eddy. Additionally the time step needs to be small enough to resolve even the fastest fluctuation. This leads to tremendous requirements in terms of computing power and mesh quality and therefore it is usually performed only for academic researches on rather small and simple geometries.

The LES represents a sort of compromise between RANS equations and DNS. It has also high demands on storage and CPU performance for unsteady and transient flows need to be computed. But still, it is less demanding than DNS and due to the fast improvement of hardware this method becomes more and more applicable, even for more complex flow problems. As the title suggest, this project concentrates mostly on this kind of simulation and therefore it will be discussed in more detail in the following.

There exist also a lot of sub-forms and mixtures of various approaches, like DES (Detached Eddy Simulation), VLES (Very Large Eddy Simulation), etc. However, to mention them here would go beyond the scope of this report.

For the project the RANS and the LES simulation have been applied. This chapter is dedicated to introduce the reader to some crucial basics of LES. It will cover the terms fine structure model and turbulence model. Due to the numerous different models and approaches, each subchapter will deal only with the methods used for this particular project [1, 2].

1.3 Basic idea of Large Eddy Simulation

Although there have been huge efforts for developing turbulence models since the early days of CFD, a model suitable for a wide range of practical applications and offering convincing results still does not exist. This is due to the very different properties of the various scales of eddies. The smaller eddies are almost isotropic and show universal behavior while the larger ones interact with and extract energy from the main flow. Their behavior is heavily dependent on the used geometry and the boundary conditions. The core principle of LES is that the larger eddies are computed with a time dependent simulation, while the smaller scales are still represented by models. How-

ever, since the smaller scales are breakdown products of the larger one and represent just a small amount of the overall energy, they are easier to model. With Reynolds-averaged equations on the other hand *all* scales need to be represented by a single turbulence model, which proves to be inaccurate, especially for the larger eddies.

The classification of *small* and *large* eddies is conducted with dedicated filter functions, which take a *cutoff* width as input parameter. When applied the filter function destroys all the information related to the eddies which are beyond this scale, while the rest remains untouched and gets computed. To describe this association the terms GS (grid scale) and SGS (sub-grid scale) are used. When the smaller scales are left out, also their effects on the flow are omitted. This effects are known as SGS stresses and have to be described by means of so-called SGS models, which are basically turbulence models.

The finer the applied filter is, the more eddies are modeled numerically and therefore the FS model can be simpler while yielding a similar accurate solution. If the filter becomes, theoretically, indefinitely small, the LES fades into a DES. The other margin case would be a very rough filter, which allows only the most energized eddies. This kind of simulation is known as VLES (Very Large Eddy Simulation).

These circumstances offer two possible options in order to improve the simulation. There can be improved either the FS model or the used grid. In most cases an improvement of the FS model is the option of choice, since a refinement of the grid leads to a much higher demand in terms of resources and comes with no warranty to provide a more accurate solution. However, one should bear in mind that, a LES is also highly dependent on the preceding inlet circumstances as well as the wall functions [1, 3].

1.4 Turbulence models

A majority of the scientific research concerning LES is dedicated to the development of the so called fine structure- or turbulence models. They are used to represent the impact of SGS eddies symbolically, by dissipating as much energy as it would be the case with a DNS model of the same problem. Most of the fine structure models used today are deterministic. Accordingly they are dependent of the velocity field and yield exactly one solution [1].

1.4.1 $k-\varepsilon$ turbulence model

The $k-\varepsilon$ models are the most frequently used and best proved turbulence models for RANS equations. The reason for their popularity is their convincing performance in confined flow, what is usually the case with industrial application. For these simulations the $k-\varepsilon$ model offers a good compromise between accuracy and robustness. In contrast to its excellent performance for many industrially relevant flows, it shows some major weaknesses when it comes to unconfined or rotating flows.

The standard $k-\varepsilon$ model presumes an isotropic turbulent viscosity and adds two extra transport equations, one for the k and one for the ε, which need to be solved alongside the RANS flow equations. The first transported variable k stands for the turbulent kinetic energy, while the ε term is responsible for the dissipation and features the dimensions m^2/s^3. With k and ε the velocity scale ϑ and the length scale l are defined as $\vartheta = k^{1/2}$ and $l = k^{3/2}/\varepsilon$. Through this identity the eddy viscosity can be obtained by

$$\mu_t = C\rho\vartheta l = \rho C_\mu \frac{k^2}{\varepsilon} \tag{1.1}$$

where C_μ is a dimensionless constant. The additional equations for k and ε are then:

$$\frac{\partial(\rho k)}{\partial t} + div(\rho k U) = div\left[\frac{\mu_t}{\sigma_k} grad k\right] + 2\mu_t S_{ij} S_{ij} - \rho\varepsilon \tag{1.2}$$

$$\frac{\partial(\varepsilon k)}{\partial t} + div(\rho\varepsilon U) = div\left[\frac{\mu_t}{\sigma_\varepsilon} grad\varepsilon\right] + C_{1\varepsilon}\frac{\varepsilon}{k} 2\mu_t S_{ij} S_{ij} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{1.3}$$

The left side of the equation deals with the rate of change of k or ε plus the transport of by convection, while the right side features the transport by diffusion plus the rate of production minus the rate of destruction of the values k and ε. C_μ, σ_k, σ_ε, $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are constants with given values for the standard $k-\varepsilon$ model that are applicable for a wide range of turbulent flows [1].

1.4.2 Smagorinsky-Lilly SGS model

The Smagorinsky-Lilly SGS model bases on the assumption that the turbulent stresses are proportional to the mean rate of strain. This approach requires the changes in the flow direction to be slow in order to balance the production and dissipation of turbulence. Furthermore the turbulence structures should be isotropic [1].

> "Thus, in Smagorinsky's SGS model the local SGS stresses R_{ij} are taken to be proportional to the local rate of strain of the resolved flow $\bar{S_{ij}} = \frac{1}{2}(\partial\bar{u_i}/\partial x_j + \partial\bar{u_j}/\partial x_i)$:" [1, p.102]

This leads to the equation

$$R_{ij} = -2\mu_{SGS}\bar{S_{ij}} + \frac{1}{3}R_{ij}\delta ij = -\mu_{SGS}\left(\frac{\partial\bar{u_i}}{\partial x_j} + \frac{\partial\bar{u_j}}{\partial x_i}\right) + \frac{1}{3}R_{ii}\delta_{ij}. \tag{1.4}$$

The additional term on the right hand side of the equation is responsible that the formula yields the correct results for the normal stresses τ_{xx}, τ_{yy} and τ_{zz}. Due to the definition of the Kronecker symbol δ_{ij}, this term becomes zero for any other stresses. The constant which determines the relation between local stresses and local rate of strain is the dynamic SGS viscosity μ_{SGS}. The Smagorinsky-Lilly model bases on Prandtl's mixing length model, which comes with the assumption that the kinematic turbulent viscosity ν_t can be expressed through the velocity scale ϑ and the turbulent length scale l by

$$\nu_t = C\vartheta l. \tag{1.5}$$

Here C is a dimensionless constant of proportionality. The dynamic viscosity μ_{SGS} can then simply be obtained by $\mu_{SGS} = \nu_{SGS}\rho$. For the length scale the cutoff width Δ, used for the filter, is the logic choice.

Hence the dynamic SGS viscosity can be taken as

$$\mu_{SGS} = \rho(C_{SGS}\Delta)^2|\bar{S}| = \rho(C_{SGS}\Delta)^2 sqrt2\bar{S_{ij}}\bar{S_{ij}} \tag{1.6}$$

Various studies proved that values between 0.1 and 0.24 for the constant C_{SGS} are appropriate, but occasionally this parameter needs adjustment in order to provide reasonable results [1].

1.5 Heat transfer

Heat is a special form of energy and is stored in the chaotic movement of atoms and molecules. In a non-adiabatic system it is the amount of energy which resigns over the border if a temperature gradient is prevailing. The transition of the heat over the system borders is therefore called heat flux and runs always in the direction of the

lower temperature [4].

Basically there are three different ways how heat can be transferred from one system to another. In practical application they usually appear combined but for computation they can be dealt with individually. Each of them will be discussed in the following.

1.5.1 Mecanisms of heat transfer

With *conduction*, heat gets transferred between particles in immediate vicinity. It occurs with adjacent molecules of solids or steady fluids. If no counteracting processes are present the temperature difference becomes sooner or later zero. The heat conduction through a solid wall can be described by means of *Fourier's law*:

$$Q = \frac{\lambda}{\delta} A \Delta t \tau \tag{1.7}$$

The heat conductivity λ is a material property and dependent from the temperature. δ is the thickness of the wall and τ the timespan.

Between moving fluids proceeds the so-called *convection*. This form of heat transfer is the dominant one in liquids and gases. It occurs in two different forms. As *free convection*, if the heat transfer itself causes the flow, which would for example be the case if air flows by a heating device. Or as *forced convection* if the movement is caused by device like a pump or a fan. This would be the case when cooling an engine.

The last form of heat transfer is by *radiation*. Radiation is the transmission of energy by means of waves. It can proceed through different materials, although no material is required for it is also capable of spreading through space. Physically, the internal energy of the radiating system is converted into multiple tiny energies, which are then emitted. The movement and location of the single photons cannot be determined, but the behavior of a mass of photons can be described by means of an electromagnetic wave. Usually the radiation is named after its way of creation, like γ-, or x-radiation. The specific radiance M of a body is given by

$$M = \varepsilon \sigma T^4 \tag{1.8}$$

, where ε is the emission coefficient and can be taken from dedicated tables. σ is a physical constant called Stefan-Boltzmann constant with a fixed value of 5.87e-8 [4].

1.5.2 Wall heat flux in Ansys CFX

The most important property, which will be investigated within this project is the wall heat flux. In Ansys CFX this variable represents the total heat flux into the domain, which consists of convective and radiate participations.

The heat flux at a wall boundary is specified by a heat transfer coefficient h_c, which is obtained from the equation

$$q_w = h_c(T_0 - T_\omega) = q_{rad} + q_{cond} \tag{1.9}$$

where T_0 is the external boundary temperature and T_ω is the temperature at the wall, which is provided explicitly in this project. Figure 1.3 visualises this circumstances [8].

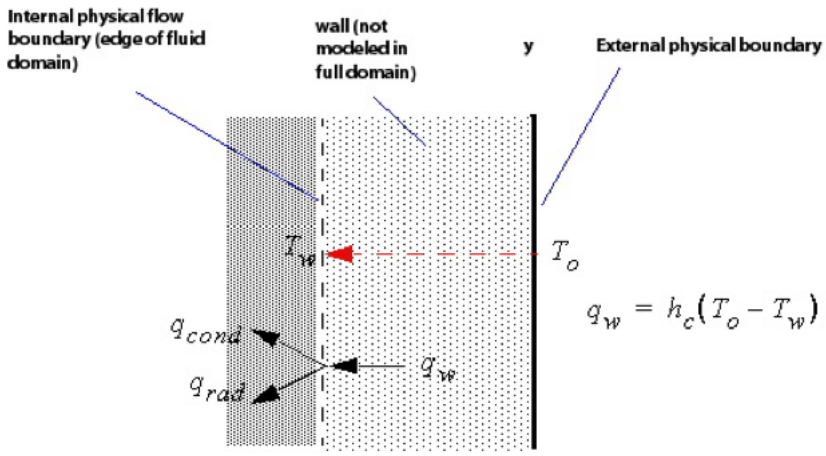

Figure 1.3: [8] Heat transfer model in Ansys CFX

1.6 Similitude of heat transfer

It is impossible to determine the heat transfer for every technical problem experimentally. Fortunately, it is possible to transfer existing results to physically similar objects from which the heat transfer coefficient can then be obtained.

The originator of this similitude theorem is Wilhelm Nußelt. The Nußelt number, which is a form of the differential equation of the heat transfer, but with dimensionless parameters, is named after him. It is the dimensionless form of the heat transfer

coefficient and given by

$$Nu = \frac{\alpha l}{\lambda} \tag{1.10}$$

Once the Nußelt number of a specific problem is known the heat transfer coefficient α can be easily calculated. The Nußelt number itself is dependent from other dimensionless numbers which describe flow- and heat transfer processes. The most important ones are the Reynolds number and the Prandtl number. The Reynolds number is capable of predicting similar flow patterns in different fluid flow situations and is defined as

$$Re = \frac{vl}{\nu} \tag{1.11}$$

where v is the characteristic velocity of the fluid, l a characteristic length of the problem (for example the inner radius of a pipe, which is flowed through by a fluid), and ν the kinematic viscosity of the fluid.

The Prandtl number is named after the German physicist Ludwig Prandtl and defined as

$$Pr = \frac{\eta c_p}{\lambda} \tag{1.12}$$

with η for the dynamic viscosity of the fluid, c_p as the specific heat and λ as the thermal conductivity. As a heavily on temperature dependent material property, it can be often found in tables of heat transfer properties. For air and many other gases a Prandtl number of 0.7 to 0.8 is common under normal circumstances. Unlike the Reynolds number, the Prandl number contains no length scale variable, but is dependent only on the fluid and the fluid state. For forced convection the Nußelt number is a function of the Reynolds- and the Prandtl number.

$$Nu = Nu(Re, Pr) \tag{1.13}$$

For many technical applications and problems the functional relation of these parameters is known. The value of the Nußelt number at the stagnation line of a cylinder with laminar flow for example is given by

$$Nu = 1.14 Pr^{0.4} Re^{0.5} \tag{1.14}$$

The Nußelt number and thus the heat transfer coefficient α increases with the Reynolds

number. This leads to an improved heat transfer at higher velocities. Table 1.1 shows, reachable, as well as for practical application common values, for the heat transfer coefficient [4].

Table 1.1: [4, p.374] Typical values for the heat transfer coefficient

	Acquireable values	Common values
Gases		
-Free convection	5 ... 25	8 ... 15
-Forced convection	12 ... 120	20 ... 60
Fluids		
-Free convection	70 ... 700	200 ... 400
-Forced convection	600 ... 12,000	2,000 ... 4,000

Chapter 2

Methods

The first section of this chapter deals with the resources used for the project, while the subsequent ones focus completely on setting up the CFD software tools and executing the actual simulation. The subchapters are divided according to the different parts of software or properties they are dealing with.

2.1 Technology used

CFD is an area with huge demands in computing power. Therefore industrial CFD calculations belong to the domain of supercomputers or HPCCs (high performance computing clusters). Everything needed for the conduction of this project in terms of hard- and software was provided in the FH Joanneum facility.

2.1.1 Hardware

The department of Aviation at the University of Applied Sciences in Graz is equipped with a HPC (high performance computing) laboratory, compromising sixteen high performance computers, capable of providing the huge amount of CPU power needed for CFD calculations.

Table 2.1 shows the properties of one of these devices.

Table 2.1: Specification of computing hardware

Central Processing Unit (CPU)	Intel® Xeon(R) CPU X5690
Architecture	x86_64
Core speed	1596 MHz
Cores	12
Random Access Memory (RAM)	23.6 GB

2.1.2 Software

The computers in the HPC laboratory feature the operating system Debian 7.8 (wheezy). Each has the software packages ANSYS ICEM CFD 14.0 and ANSYS CFX 15.0 installed, which were used for performing the simulation. Additionally, minor calculation, as well as the analysis and visualization of the results was done with MATLAB®.

ANSYS ICEM CFD 14.0 is an effective software tool for generating, improving and repairing CAD (Computer Aided Design) meshes. Its primary function however is the generation and enhancement of meshes, which are necessary for the flow simulation. Therefore it allows the import from various different CAD software and is able to export the mesh for several different CFD solvers such as ANSYS CFX.

ANSYS CFX 15.0 is the software tool used for conducting the simulation. It is a high-performance CFD program for many different fluid flow problems and comes with a highly potent and intuitive GUI. There are three different subprograms for individual simulation tasks. *ANSYS CFX 14.0 Pre* is responsible for setting up initial conditions, solver settings and the like, while *ANSYS CFX-Solver Manager 14.0* deals with the actual solving of the equations for the individual meshes and time steps. The third one, *ANSYS CFX CFD-Post 14.0*, is used for the post-processing and analysis of finished calculations and is capable of three-dimensional visualization of the results, as well as performing various calculations and drawing charts.

The following subchapters are divided according the software tools, used for the particular steps.

2.2 Mesh generation with Ansys ICEM 14.0

The meshed NACA 0012 airfoil was provided as two-dimensional C-grid domain by Dr. Hassler as it can be seen in figure 2.1. It is meshed with hexahedral elements and features a total of 219,000 elements. The domain features physical measurements

of 7m by 5m by 0.01m and the wing profile inside the domain comes with a chord length of 1m. Due to the nature of the profile with a maximum thickness of 12%, the thickness is 0.12m in total values. On the left side is located the inlet, on the right the outlet and the upper and lower borders are defined as walls, as it can be seen in figure 2.1. Figure 2.2 features a close-up on the enormous grid refinement at the airfoil surface.

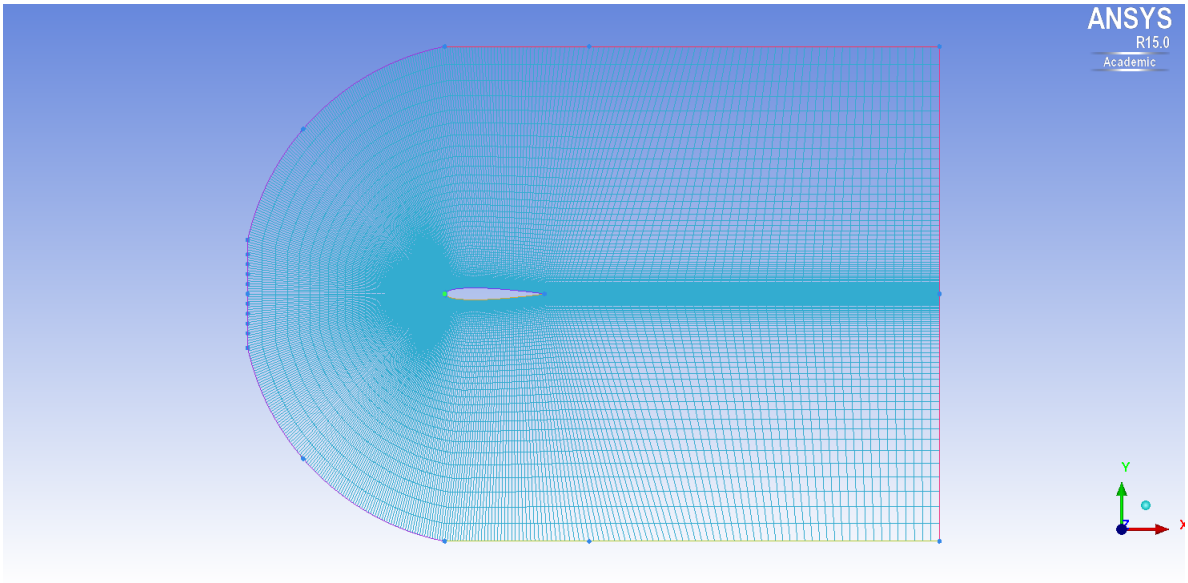

Figure 2.1: Provided domain with mesh refinement in vicinity of the wing surface

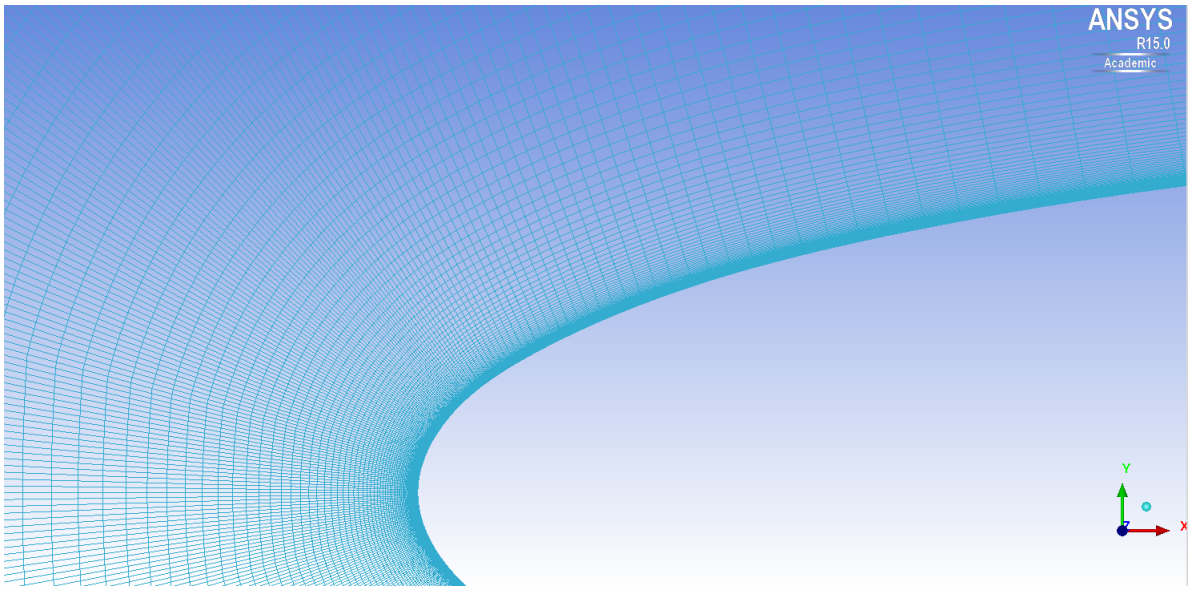

Figure 2.2: Close-up to the mesh at the airfoil surface

Due to the three-dimensional characteristics of the large eddies this two-dimensional mesh was not sufficient, but had to be extended in the third dimension in order to be capable of providing convincing results. This was achieved by simply extending the

given mesh in the third direction by thirty elements, resulting in a physical thickness of 0.30m in z-direction. This leads to a total of 2,263,000 elements and 2,172,810 nodes. In figure 2.3 the final mesh is visible in an isometric view with the airfoil in the center. The properties of the final mesh, as it was exported from Ansys ICEM 15.0 are listed in table 2.2.

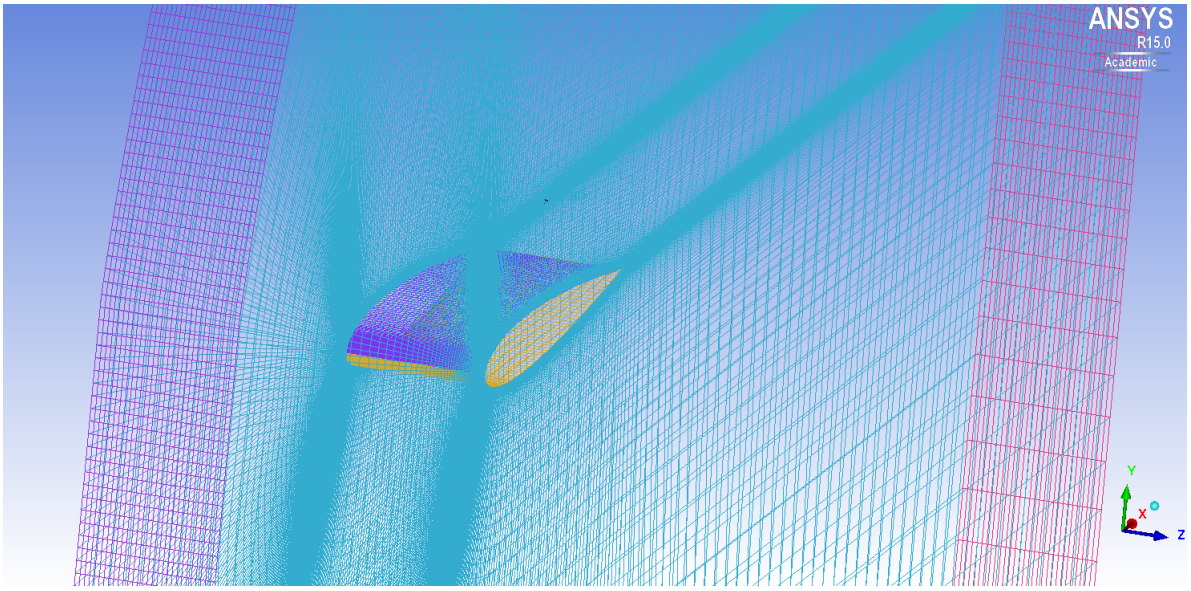

Figure 2.3: Close-up of the meshed geometry in isotropic view

Table 2.2: Properties of the mesh

Domain length	7m
Domain height	5m
Domain width	0.3m
Profile chord length	1m
Maximum profile thickness	0.12m

2.2.1 y⁺ value

The y^+ value is the dimensionless wall distance and an important factor for evaluating the physical accuracy of the flow in vicinity of a wall. It is connected with the frictional velocity u_τ and the kinematic viscosity ν by

$$y^+ = \frac{\rho u_\tau y}{\mu} \tag{2.1}$$

with y for the orthogonal offset from the wall. u_τ is then given by

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}} \tag{2.2}$$

The wall shear stress τ_w can be obtained by the following formula

$$\tau_w = \frac{1}{2} C_f \rho U^2 \tag{2.3}$$

with C_f as the skin friction coefficient which must be taken from empirical results, ρ as the density and U as the mean velocity of the main flow. A good estimation for internal flows is $C_f = 0.079 Re^{-0.25}$.

For the Large Eddy Simulation it is crucial to score a y^+ value at around 1.0 or below. In order to evaluate the height of the first cell, necessary to achieve a certain y^+ value equation 2.1 can be transformed to

$$\Delta y_1 = \frac{y^+ \mu}{\rho u_\tau} \tag{2.4}$$

with the first cell height Δy_1.

Although the y^+ value is dependent from time and location for simple geometries and flows, such as the one used for this rough estimate, this correlation is highly accurate [1, 2, 7].

For the calculation of the Δy_1 value a short MATLAB® script has been applied. It yielded a result of 8.02e-6 for the height of the cell in immediate vicinity of the wing surface. An investigation of the given geometry in Ansys ICEM 15.0 (figure 2.4) showed that the height of this cell features a cell height of 9.55e-7, which is already beneath the desired value and therefore a refinement of the two-dimensional mesh was not necessary.

2.3 Simulation setup in Ansys CFX-Pre 15.0

There have been two simulations set up in Ansys CFX-Pre, linked together with *Simulation Control*. The first one was a stationary RANS simulation with the task to provide a fully developed flow field as initial condition for the subsequent LES. In Ansys CFX-Pre they were entitled according to their simulation type “Stationary” and “Transient”.

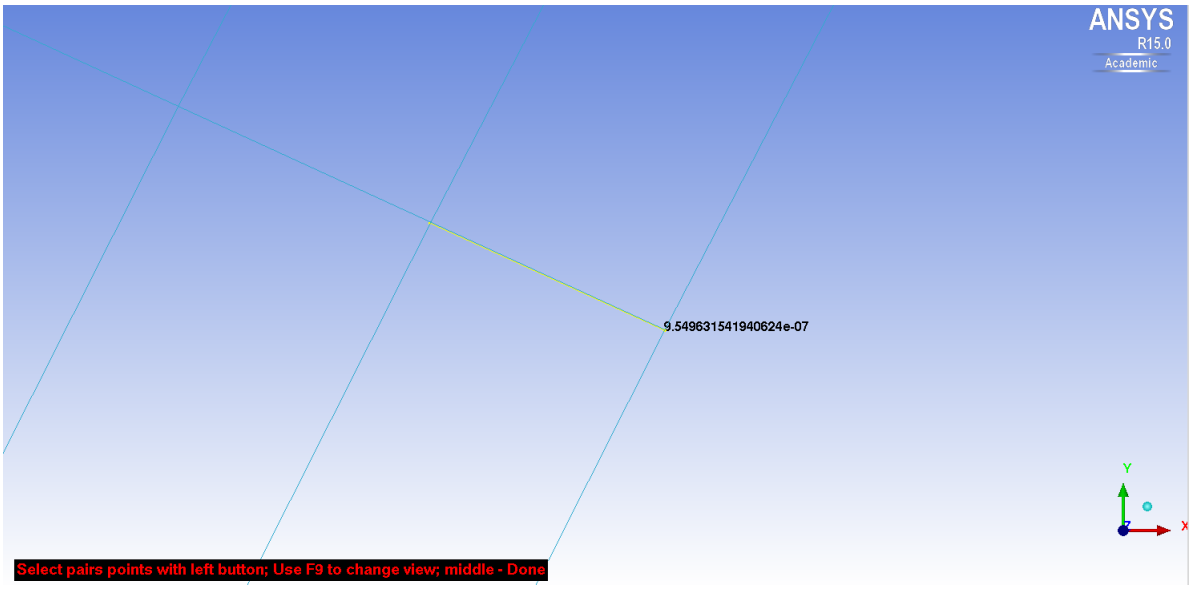

Figure 2.4: Measurement of the height of the cell next to the wing surface

Each simulation has the properties described in the following chapters for themselves. However, since they are mostly the same for either simulation, there will be no strict distinction between the two of them, but it will be referred to explicitly, if there have been differences in the adjustments.

2.3.1 Domain

The CFD software requires a specific area where the equations for each method can be evaluated. Usually the object of interest is located inside the domain and at the borders of a domain are applied so-called boundary conditions, responsible of defining the borders of the area of investigation. In Ansys CFX one or more fluid models can be defined for a domain. These are used to describe and adjust the fluid dominating in this area. For this project only one fluid model was necessary, featuring air at twenty-five degrees. The turbulence model of the fluid however was different for stationary- and transient simulation. While the stationary one was based on the $k - \varepsilon$ model, the transient applied the LES Smagorinsky model.

2.3.2 Analysis type

For the transient analysis a number of time steps and duration of the time steps themselves had to be considered. For the amount of time steps an initial quantity of 20,000 was chosen. For adjusting the necessary time step value the so-called CFL (Courant-

Friedrichs-Lewy) number was investigated, which proves to be a good measurement for accuracy. In order to provide reliable and stable results an average CFL number in the range of 0.5 to 1.0 is demanded. There are also stable results possible with higher CFL number, but the turbulences may be damped and the result distorted.

After starting the solving with various different timstep values it settled on a value of 1e-5 seconds, which lead to an equivalent Courant number of 0.87.

2.3.3 Boundary conditions

In total there have been seven boundary conditions defined. The first one is for the inlet conditions and provides a constant inlet velocity at the western front of the domain. Instead of an outlet, an opening was specified on the eastern border. This is the option of choice for turbulent flows, allowing backflows of the fluid to reenter the domain, instead of just leaving. The northern and southern walls were defined as free-slip walls and the wing surface as no-slip wall, leading to a velocity of zero on surface of the wing. Two symmetry conditions at the front- and the backside completed the closure, simulating a theoretical infinite expansion in z-direction.

2.3.4 Initial conditions

As initial inlet velocity, 66.8m/s was specified. Furthermore the relative pressure was set to zero, meaning that the initial pressure in the domain equals the pressure prevailing at the outlet. In Simulation Control it was declared that the LES simulation uses also the developed flow field of the preceding RANS simulation as initial condition.

2.3.5 Solver control settings

For the Advection Scheme for the LES was chosen *Specific Blend Factor*. This scheme allows using a mixture of the High Order Advection Scheme and the CDS (Central Difference Scheme). The relation between these two techniques is controlled via the Blend Factor [10]. For the start a Blend Factor of 0.5 was chosen, meaning that the schemes were used in equal shares. In advance of the solving this factor was altered according to table 2.3, in order to favor more and more the CDS, which would have been the intended choice for the transient simulation.

Another setting needed for transient simulations is the number of coefficient loops. This is the maximum number of times the equations are iterated for a single time step.

> "The implicit coupled solver used in CFX requires the equations to be converged within each timestep to guarantee conservation. The number of coefficient loops required to achieve this is a function of the timestep size. With CFL numbers of order 0.5-1, convergence within each timestep should be achieved quickly. It is advisable to test the sensitivity of the solution to the number of coefficient loops, to avoid using more coefficient loops (and hence longer run times) than necessary." [9]

As an initial setting the number of maximum coefficient loops has been set to 10. However, if the size of the time step requires more than tree to five coefficient loops the result can be considered as inaccurate. As convergence criteria a root mean square of below 1e-6 of the residual target has been demanded. This can be considered as the minimum required accuracy for a LES in order to achieve scientific relevant results.

Table 2.3: Adjustment of the blend factor with respect to the time step interval

Time step interval	Blend factor
1 ... 10,000	0.5
10,001 ... 15,000	0.3
15,001 ... 18,555	0.1

2.3.6 Output control

Due to numerous time steps and the resulting large amount of data, only the results of every tenth time step have been permanently saved to the disk. Moreover the output of the *Transient Results* have been limited to the properties Pressure, Wall Heat Flux and Force in x-direction for further decreasing the necessary storage. For easy recovery after a shutdown or the like, a full backup has been conducted automatically every hundredth time step.

2.3.7 Simulation control

The sequence of the simulations and their relationship has been specified by means of the *Simulation Control*. The stationary simulation was executed first with given initial

conditions. The transient simulation followed subsequent and was able to benefit from the fully developed flow field of the preceding simulation.

2.4 Solving with Ansys CFX-Solver-Manager 15.0

The solver setup has been specified as full run with double precision checked in order to receive more exact results. The chosen technique was Intel MPI Distributed, which allows the usage of multiple machines on the local network. In total six computers of type described in table 2.1 have been applied for executing the solving.

Due to the provided settings the solver started with the stationary simulation, which finished normally. Thereafter the transient one was conducted. It was aborted after 18,555 time steps, because a review of the latest results showed that the simulation has already reached a kind of steady state and thus no more time steps were needed. In total it took 1.307e6 seconds (15 days, 3 hours, 3 minutes, 58 seconds) to calculate all 18,555 time steps and writing 1,855 transient result files and 185 backup files.

Chapter 3

Results

With a time step duration of 1e-5 seconds all time steps combined make up a physical simulation duration of 0.19s. Although this seems to be a rather short timespan, it proves to be sufficient, because with a velocity of 66.8m/s the flow passes the wing surface with a length of 1m five times during this simulation time.

The content of this chapter deals with the investigation of the last 200 time steps.

3.1 Checking accuracy requirements

The post-processing was conducted with Ansys CFX-Post 15.0. The first thing was checking whether the y^+ value on the wing surface was within the correct scope. This was done by plotting the value on the wing surface as it can be see in figure 3.1. Obviously it is nowhere beyond one and hence this requirement is fulfilled.

Additionally the drag coefficient of the wing was mirrored over the last time steps. When it does not change any more, it can be assumed that the simulation has reached a kind of steady state. The value for the drag coefficient was calculated in Ansys CFX-Post by the equation [5]

$$C_D = \frac{F_{horizontal}}{\frac{1}{2}\rho U^2 A_{eff}} \tag{3.1}$$

where A_{eff} is the projection of the wing geometry in flow direction and $F_{horizontal}$ the force operating in x-direction. The values for the drag coefficient for the last 200 steps are listed in table 3.1. It can be seen that they stay the same, apart from some minor deviations.

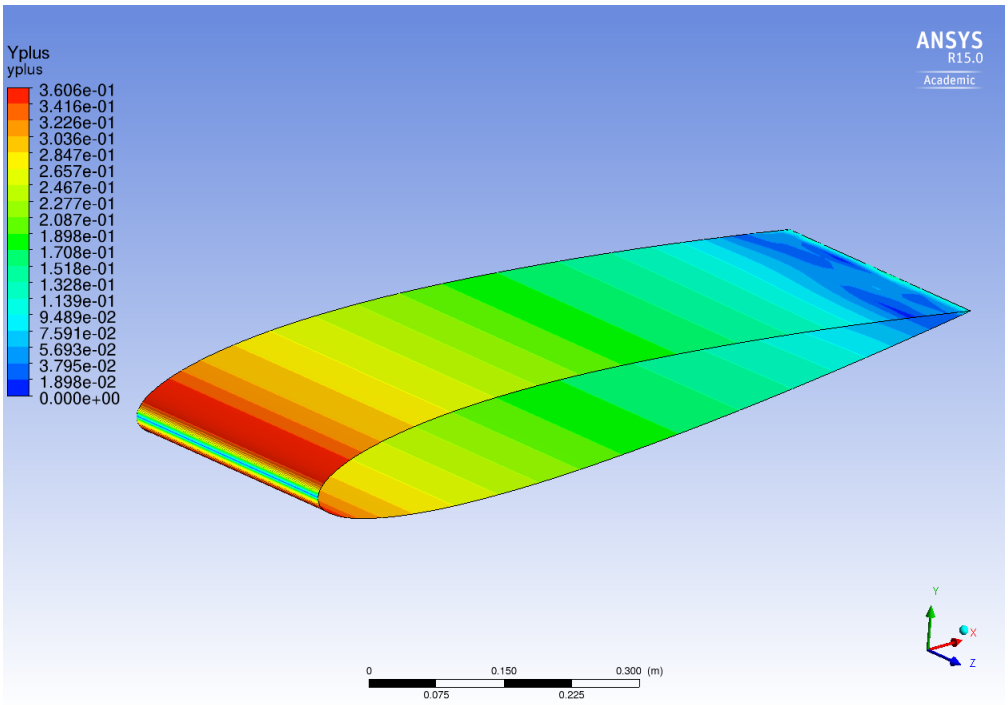

Figure 3.1: The y^+ value on the airfoil surface

3.2 Exporting data from Ansys CFX-Post

For investigating the heat transfer a polyline was inserted exactly at the middle of the airfoil. It was obtained by intersecting the wing surface with a xy-plane, which was positioned at 0.15m in z-direction. Subsequent the properties x-coordinate and Wall Heat Flux on this polyline were exported as csv file. This file served as input for MATLAB® and was used for the visualization of the results.

For comparison and evaluation purpose the same flow problem was simulated by Dr. Hassler by means of a RANS simulation. The result file of this simulation was treated the same way, so that there could be exported a csv file with the stationary data as well.

3.3 Processing in MATLAB®

As next step the csv files were imported into MATLAB®, where the data was extracted and used for plotting the wall heat flux over the length of the profile. For comparison reasons both results, the stationary as well as the transient one, were displayed in the same plot, which can be observed in figure 3.2.

This data for the heat transfer was the basis for the calculation of diverse dimen-

Table 3.1: Variation of the drag coefficient over the last 200 time steps

Time step	Drag coefficient
18,450	0.104639763906978
18,460	0.104639857472925
18,470	0.104639857472925
18,480	0.104640124290383
18,490	0.104640333687198
18,500	0.104640527598881
18,510	0.104640735058614
18,520	0.104640635962194
18,530	0.104640528407586
18,540	0.104640719551398
18,550	0.104640922019082

sionless numbers, which were of major importance for the evaluation of the simulation. In detail, the Nußelt and the Froude number were used for comparison. For a cylinder the Froude number is more or less equal to one. This was utilized for the evaluation, because the nose of the airfoil can be compared to a cylinder. The Nußelt and Froude number have been computed with three different approaches. For the first, the Nußelt number for a cylinder, equal to the airfoil nose diameter, was generated by means of the Prandtl and the Reynolds number with the relation given in equation 1.14. This was done for comparison reason with a typical specific heat transfer coefficient of 1,005 Joules per kilogram Kelvin applied. For the other two approaches the Nußelt number was computed from the values extracted from the simulation. Particularly the values of the wall heat flux at the stagnation point, where x is equal to zero, were of special interest. The stationary simulation yielded a value of 253.69 Watt per square meter at this point and the transient one a value of 257.05 Watt per square meter. These were used for computing the heat transfer coefficient α, which can be obtained through the correlation

$$\alpha = \frac{q}{\Delta t} \tag{3.2}$$

with Δt as the difference of the temperatures of wall and fluid [4]. With respect to the initial settings it was one degree. The airfoil nose diameter served as specific length scale, given by the radius $R_{LE} = 1.1019t^2$ times two, with t as the maximum profile height. The Nußelt number was then calculated by means of equation 1.10. In table 3.2 the differences and similarities of the single approaches can be observed.

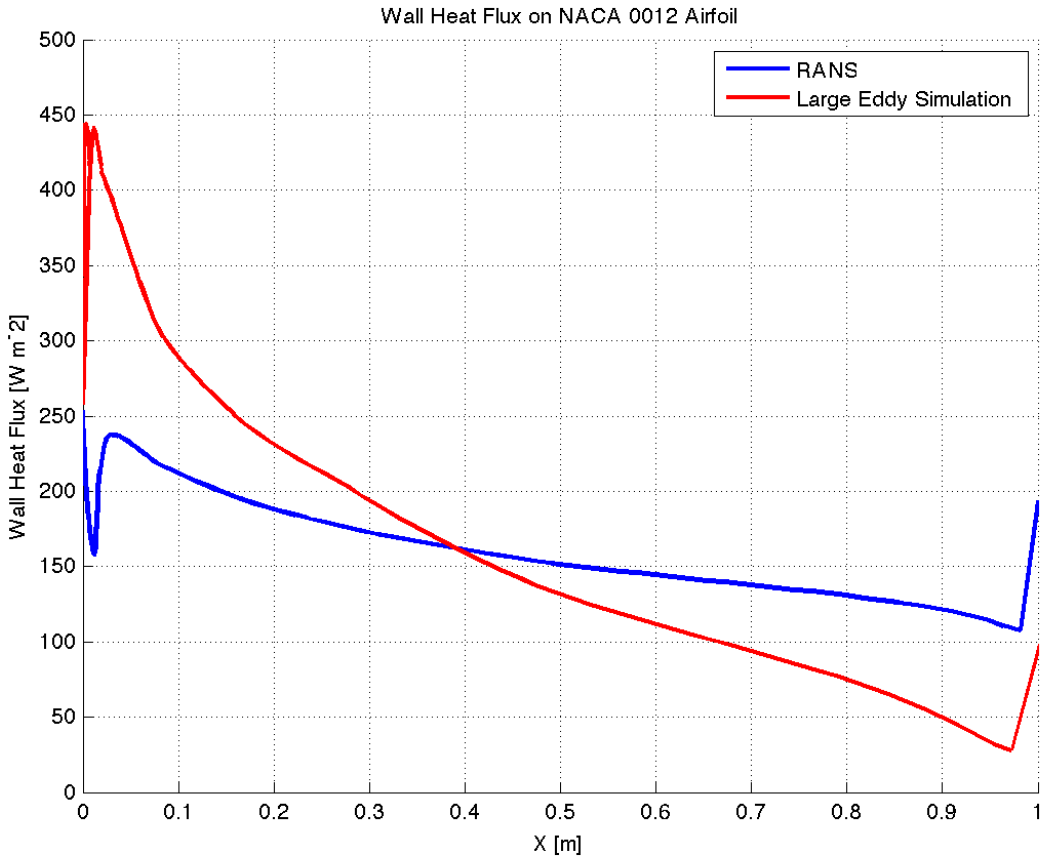

Figure 3.2: Distribution of the wall heat flux on the wing surface along the x-axis

Table 3.2: Dimensionless coefficients resulting from the simulation

	Values for a cylinder	RANS results	LES results
Reynolds number		134,000	
Prandtl number	0.7141	-	-
Nußelt number	364.72	308.94	313.03
Froude number	0.9963	0.8439	0.8551
α, W/m^2 K	257.05	253.69	299.50

Chapter 4

Discussion

As mentioned in the abstract the aim of this project is the conduction of a heat transfer by means of a Large Eddy Simulation, afterwards comparing the obtained results with the results of a RANS simulation of the same flow problem and analyzing deviations and similarities, as well as evaluating the applicability of the LES for technical flow investigation.

4.1 Investigation of the wall heat flux

As basis for the inspection and evaluation served the wall heat flux on the wing surface. The examination relied on the results obtained from the simulations, which are plotted in Figure 3.2 and the calculation results, belonging to them, in table 3.2. Although in this plot it seems like there is just one graph per simulation type, there are actually two for each - one for the upper side and one for the bottom side of the wing. However, due to the symmetry of the geometry and the flow conditions their heat transfer along the profile is almost the same, appart from minor numerical inaccuracies.

The heat transfer resulting from the RANS equations features a heavy flunctuation at the front end of the airfoil. This is physically illogically and results most likely from the application of the SST (Shear-Stress Transport) turbulence model for this simulation. The LES results seem more convincing in this respect and it can be oberved that they feature a much higher wall heat flux at the front section of the wing and a lower one at the rear section, while it is equal to the stationary simulation at about forty percent wing depth. This agrees with the exectations, because in a turbulent flow the heat transfer is much better than in a laminar flow for the turbulent vortices movement favors the

energy exchange [1].

4.1.1 Interpretation of the dimensionless numbers

This subchapter is dedicated to analysing of the dimensionless number refered to in table 3.2. The Reynolds number is of course the same for all solutions since it is independent from heat transfer. The parameter of interest is the Foude number, which is almost equal to one for a cylinder. For the transient solution the Froude number shows a deviation of about fourteen percent from this value. What causes this inaccuracy may be the subject of further investigations, but an interesting fact here is, that it is still closer to the desired result than the stationary simulation.

4.1.2 Comparison Large Eddy Simulation and RANS equation

As already mentioned the Large Eddy Simulation requires massive resources and a very sophisticated mesh compared to the RANS equations. However there are significant reasons, why LES becomes more and more attractive than RANS. One major drawback of the RANS equations is, that they are not sufficiently reliable in terms of prediction of heat transfers, as it is the case with this simulation, where the RANS equations come up with a physically rather questionable behavior of the heat transfer distribution.

On the other hand one should be aware of that a slightly inappropriate modelling of the LES can easily lead to completely wrong results. Accordingly LES requires a deeper knowlege of the subject, but in return it is capable of dealing with plenty of different flow conditions, without relying on a priori assumptions [1, 3].

Chapter 5

Conclusion

Unfortunately there were nowhere experimental results of a heat transfer on a NACA airfoil to be found and therefore the LES method could only be evaluated by comparing with other CFD results. Accordingly one interesting task for future investigations would be the comparison of the results from this project to experimentally achieved results.

Furthermore it has to be stated that the documentation and reference material for the Large Eddy Simulation is rather meager and it seems that the Ansys Software tool are more dedicated to stationary simulations. Due to the long calculation durations it appears rather cumbersome and errors in the simulation setup can cost a vast amounts of time. Therefore it became obvious that LES requires more experience and knowledge in CFD in order to produce reliable results

Nevertheless there are various reasons to prefer the LES, as stated in chapter 4.1.2, and thus it is most likely to become more frequently applied for technical flow investigation in the future.

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[9] SAS IP, Inc., "The Large Eddy Simulation Model (LES)," [web site], URL: http://www.arc.vt.edu/ansys_help/cfx_
mod/i1303019.html [cited 15 March 2015].

[10] ANSYS, Inc., "ANSYS CFX-Solver Theory Guide,", Southpointe, 2009.

Appendix A

Appendix

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Title:            cell_height.m
% Version:          2.2
% Author:           Stefan Lengauer
% Date:             16th February 2015
% Description:      File for computing the necessary cell height for the
%                   cells attached to the wing surface.
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;
close all;

% Definition of variables
rho = 1.168;     % Density, [kg m^-3]
U = 66.8;        % Velocity, [m/s]
L = 1;           % Characteristic length scale, [m]
mu = 18.48e-6;   % Dynamic viscosity [Pa*s]
yplus = 1;       % y+, dimensionless

Re = rho * U * L / mu;
Cf = 0.079 * power( Re, -0.25 );

Tau_w = 1/2 * Cf * rho * power( U, 2 );

Utau = sqrt( Tau_w / rho );
Δy = yplus * mu /( rho * Utau );
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Title:              wall_heat_flux_plot.m
% Version:            1.0
% Author:             Stefan Lengauer
% Date:               15th February 2015
% Required Files:     wall_heat_flux_stationary.csv
%                     wall_heat_flux_transient.csv
% Description:        Script for creating and saving the data plots
%                     obtained from CFX-Post.
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;
close all;

%% Data Import
STAT = csvread( '../simulation_data/wall_heat_flux_stationary.csv' );
TRANS = csvread( '../simulation_data/wall_heat_flux_transient.csv' );

x_stat = STAT( :, 1 );
y_stat = STAT( :, 4 );

x_trans = TRANS( 3:350, 1 );
y_trans = TRANS( 3:350, 4 );


%% Plot
hold on;
grid;

plot( x_stat, y_stat, 'linewidth', 2, 'color', 'blue' )
plot( x_trans, y_trans, 'linewidth', 2, 'color', 'red' )

axis( [0, 1, 0, 500] );
title( 'Wall Heat Flux on NACA 0012 Airfoil' )
legend( 'RANS', 'Large Eddy Simulation' )
xlabel( 'X [m]' )
ylabel( 'Wall Heat Flux [W m^-2]' )

%% Save Plot
saveas( figure(1), '../images/Wall_Heat_Flux_Plot.png', 'png' )
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Title:            dimensionless_coefficients.m
% Version:          1.3
% Author:           Stefan Lengauer
% Date:             3rd March 2015
% Description:      Script for computation for the dimensionless
%                   coefficients, necessary for the evaluation of the
%                   results.
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all;
close all;

% Simulation parameters

c = 1.0;                % Chord length, [m]
t = 12/100;             % Maximum profile height, [m]
w = 66.8;               % Fluid velocity, [m s^-1]

tw = 26 + 273.15;       % Temperature at the wing surface, [K]
tf = 25 + 273.15;       % Temperature of the fluid, [K]
A = 0.5967;             % Wing surface, [m^2]
whf_trans = 257.0520;   % Wall heat flux at stagnation point from transient
                        % simulation, [W m^-2]
whf_stat = 253.6925;    % Wall heat flux at stagnation point from
                        % stationary simulation, [W m^-2]

% Material properties for air at 25C

cp = 1007;              % Heat transfer coefficient, [J kg^-1 K^-1]
eta = 18.48e-6;         % Dynamic viscosity, [kg m^-1 s^-1]
lambda = 26.06e-3;      % Thermal conductivity, [W K^-1 m^-1]
ypsilon = 15.82e-6;     % Kinematic viscosity, [m^2 s^-1]



R_LE = 1.1019 * power( t, 2 );  % Radius Leading edge, [m]
l = R_LE * 2;                   % Characteristic length scale, [m]


% Reynolds number
Re = w * l / ypsilon;

%% Theoretical values according to the fluid properties

% Prandtl number
Pr_id = cp * eta / lambda;

% Nusselt number
Nu_id = 1.14 * power( Pr_id, 0.4 ) * power( Re, 0.5 );

% Froude number
Fr_id = Nu_id / power( Re, 0.5 );

% Heat transfer coefficient
alpha_id = Nu_id * lambda / l;
```

```
%% Values with the Heat Transfer coefficient obtained from the transient
% simulation

% Heat transfer coefficient
alpha_stat = whf_trans / ( tw - tf );

% Nusselt number
Nu_stat = alpha_stat * l / lambda;

% Froude number
Fr_trans = Nu_stat / power( Re, 0.5 );

%% Values with the Heat Transfer coefficient obtained from the stationary
% simulation

% Heat transfer coefficient
alpha_stat = whf_stat / ( tw - tf );

% Nusselt number
Nu_stat = alpha_stat * l / lambda;

% Froude number
Fr_stat = Nu_stat / power( Re, 0.5 );
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Title:            drag_coefficient.m
% Version:          1.3
% Author:           Stefan Lengauer
% Date:             13th February 2015
% Required Files:   force_x_18450.csv
%                   force_x_18460.csv
%                   force_x_18470.csv
%                   force_x_18480.csv
%                   force_x_18490.csv
%                   force_x_18500.csv
%                   force_x_18510.csv
%                   force_x_18520.csv
%                   force_x_18530.csv
%                   force_x_18540.csv
%                   force_x_18550.csv
% Description:      Script for computing the drag coefficient of the
%                   airfoil for the last 100 timesteps.
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


rho = 1.1839;           % density of air at 25 degrees, [kg m^-3]
u = 66.8;               % inlet speed, [m s^-1]
max_thickness = 0.12;   % max thickness of the profile, [m]
width = 0.3;            % profile width, [m]


% initialization of the coefficient vector
CD = zeros( 1, 11 );

for i = 450:10:550
    file = strcat( '../simulation_data/force_x_18', int2str( i ), ...
        '.csv' );
    A = csvread( file );
    force_x = A(:,4);

    % computation of the drag coefficient
    index = ( i - 450 )/10 + 1;
    CD(index) = sum( force_x ) / ...
        ( 1/2 * rho * power( u, 2 ) * width * max_thickness );
end
```

FH | JOANNEUM
Luftfahrt / Aviation

Bachelor's Thesis

Safety as Service

Service oriented Architectures for safety-critical Systems

Submitted by:	Stefan Lengauer
Registration number:	1210587029
Academic Assessor:	FH-Prof.Dipl.Ing.Dr. Holger Flühr
Date of Submission:	10 September 2015

Declaration of Academic Honesty

I hereby affirm in lieu of an oath that the present bachelor's thesis entitled

"Safety as Service - Service oriented Architectures for safety-critical Systems"

has been written by myself without the use of any other resources than those indicated, quoted and referenced.

Graz, 10 September 2015

Stefan LENGAUER,

Preface

This thesis was written as result of an internship at VIRTUAL VEHICLE at Inffeldgasse, Graz from April to July 2015, which was conducted as part of the Degree Programme in Aviation at FH JOANNEUM in Graz, Austria.

The VIRTUAL VEHICLE research center is an international company, specialized in automotive and rails industry. In total, it has more than 200 employees and concentrates on the four main research areas *Thermo- & Fluid Dynamics*, *Mechanics & Materials*, *NVH & Friction* and *E/E & Software*. For the time of my employment I worked as member of the Electrics/Electronics (E/E) & Software area, with an emphasis on functional safety. I was assigned to the European project EMC2, a part of the ARTEMIS programme which focuses on embedded multi-core systems for mixed criticality applications in dynamic and changeable real-time environments.

This thesis consists to a great extent of two documents which were produced during this internship. The first document is a glossary, which aims at defining certain terms and unifying the opinions from different research areas. The second document contains an extensive investigation on how the service oriented architecture paradigm can be applied in a safety-critical embedded systems like vehicles.

Although the employment was oriented towards the automotive industry, the investigated functional safety and fault tolerance concepts reappear in a very similar way in other engineering disciplines, like aviation. Furthermore, the service oriented approach, which is here considered with respect to automotive, could also become an important issue for aviation in near future.

At this point I want to thank my supervisor from FH JOANNEUM, FH-Prof. Dipl.Ing. Dr. Holger Flühr, my supervisor provided by the company, Dipl.Ing. Helmut Martin, as well as my project team members Dipl.Ing.Dr. Andrea Leitner and Mr. Mario Driussi, who supported me in developing the ideas and concepts featured in this thesis during numerous meetings and discussions.

Contents

Abstract

One of the major issues in the automotive and aeronautics industry is the constantly growing complexity of E/E (Electrics/Electronics) systems and the thereof resulting fault propagation due to the strong interconnection of the systems. The area of *functional safety* is concerned with the prevention of non tolerable risks in the event of error. This is conducted by identifying possible hazards, estimating the potential risks and developing necessary countermeasures, based on these investigations. These processes require an accurate and thorough comprehension of the observed E/E system.

The service oriented architecture is a design paradigm, which focuses on the concept of software reuse by implementing functionalities as technology independent and loosely coupled services. Although this architectural style is already widely applied in web applications, it has not yet found its way into safety-critical embedded systems.

This Bachelor's thesis investigates the applicability of service oriented architectures for such systems, with a focus on *functional safety* and *fault tolerance* context. The first part of the thesis mainly deals with terms that are crucial for the subsequent presented concepts, and investigates them with respect to embedded systems. On this basis it is defined what *safety as a service* can mean in general, and how the actual implementation in a given safety-critical system may look like, in order to meet with the requirements specified in the ISO 26262 standard. The ISO 26262 standard is an international safety standard for safety-critical E/E systems in vehicles with a maximum gross weight of 3.500 kg.

Kurzfassung

Eine der großen Harausforderungen der Automobil- und Luftfahrtindustrie ist die konstant zunehmende Komplexität von elektronischen Systemen und die dadurch entstehende Fehlerfortpflanzung aufgrund der weitgehenden Vernetzung dieser. Der Bereich der funktionalen Sicherheit beschäftigt sich mit der Vermeidung von nicht tolerierbaren Risiken im Fehlerfall. Dies wird durch die Identifizierung von möglichen Gefahren, der Abschätzung von potentiellen Risiken und, basierend darauf, der Entwicklung von notwendigen Gegenmaßnahmen gewährleistet. Diese Prozesse setzen ein detailiertes und umfassendes Verständnis der betrachteten elektronischen Systeme voraus.

Die serviceorientierte Architektur ist ein Designprinzip, das sich auf das Konzept der Wiederverwendung von Software konzentriert. Dies wird durch die Implementierung von Funktionalitäten als technologieunabhängige und lose gekoppelte Services bewerkstelligt. Obwohl dieser Architekturtyp bereits weitgehend für Webanwendungen eingesetzt wird, hat er noch nicht in sicherheitskritische eingebettete Systeme Einzug gehalten.

Diese Bachelorarbeit untersucht die Verwendung von Serviceorientierten Architekturen in solchen Systemen und legt dabei einen Schwerpunkt auf funktionale Sicherheit und Fehlertoleranz. Der erste Teil der Arbeit definiert einige Begriffe, die für das Verständnis der vorgestellten Konzepte ausschlaggebend sind, und untersucht sie im Bezug auf eingebettet Systeme. Darauf basierend wird deffiniert was *Sicherheit as Service* im Allgemeinen bedeuten kann, und wie die schlussendliche Implementierung in ein bestehendes System aussehen könnte, um die Auflagen des ISO-Standards ISO 26262 zu erfüllen. Der ISO 26262 Standard ist ein internationaler Standard für sicherheitskritische elektronische Systeme in Fahrzeugen mit einem maximal zulässigen Gesamtgewicht bis 3,500 kg.

List of Figures

List of Abbreviations

ADC . . . . . Analog Digital Converter
API . . . . . Application Programmers/Programming Interface
ASIL . . . . . Automotive Safety Integration Level
CAN . . . . . Controller Area Network
CBSE . . . . . Component Based Software Engineering
CP . . . . . Communication Profile
E/E . . . . . Electrics/Electronics
ECR . . . . . Error Containment Region
ECU . . . . . Engine Control Unit
ES . . . . . Embedded System
ESoA . . . . . Embedded Service oriented Architecture
HMI . . . . . Human-Machine Interaction
HTML . . . . . Hyper Text Markup Language
IA . . . . . Information Assurance
IDD . . . . . Interface Design Description
IEC . . . . . International Electrotechnical Commission
II . . . . . Information Infrastructure
ISO . . . . . International Organization for Standardization
LIF . . . . . Linking Interface
MISRA . . . . . Motor Industry Software Reliability Association
MPSoC . . . . . Multiprocessor Systems on Chip
MTTF . . . . . Mean Time To Failure
MTTR . . . . . Mean Time To Repair
SD . . . . . Service Description
SM . . . . . System Management
SP . . . . . Semantic Profile

SW . . . . . Software
SW-C . . . . . Software Component
SoA . . . . . Service oriented Architecture
SoS . . . . . System of Systems
SoSD . . . . . SoS Description
SoSDD . . . . . SoS Design Description
SysD . . . . . System Description
SysDD . . . . . System Design Description
TDI . . . . . Technology Dependent Interface
TII . . . . . Technology Independent Interface
TMR . . . . . Triple Modular Redundancy
WDT . . . . . Watch Dog Timer
WSDL . . . . . Web Service Description Language
XML . . . . . Extensible Markup Language

Chapter 1

Introduction

The SoA (Service oriented Architecture) design principle is a promising design philosophy which features a lot of advantages over the static and vendor dependent architectures, which are implemented in today's vehicles and aircraft. Hence, it is not surprising that there have already been various projects dealing with the application of SoAs in real-time embedded systems. Those include *SIRENA*, *SOCRATES*, *OASiS*, *MORE*, *RUNES* and ε*SOA* [11] [12] [13]. However, they do not address the necessary functional safety and fault tolerance requirements, which are preceding in vehicles. **Work Package 1**, "Embedded System Architectures", of the EMC2 project is dedicated to the investigation of these very issues, as this design paradigm might give way to a new generation of vehicles which are able to interconnect and operate autonomously.

One of the most important sources for this thesis was the ISO 26262 standard. Emerging from the IEC 61508 standard, the ISO 26262 standard is an international functional safety standard for series production passenger cars with a maximum gross weight of 3.500 kg. It is the state of the art for vehicles and does not set any requirements in terms of performance of equipment, but is only concerned with possible malfunctions. In total the standard features ten parts. **Part 1**, which defines all the related terms and vocabulary, **part 3** which deals with the concept phase, and **part 4**, which is dedicated to the development at system level have been of particular relevance [14] [15] [16].

The standard does not issue any regulations concerning SoA, but only provides certain requirements which have to be fulfilled. Nevertheless, there are no prescriptions on how they should be fulfilled [1].

Another important source of information was AUTOSAR. The term AUTOSAR is ambiguous as it can denote either the technical product (**AUT**omotive **O**pen **S**ystem **AR**chitecture),

or the related development partnership [17]. The partnership was founded in 2003, with its members covering more than 80% of the production of cars worldwide [18] [19]. They provide a standard which aims at establishing an industry norm for automotive software architecture. This allows different partners, as well as suppliers and manufacturers, to collaborate without any obstacles in terms of languages or methodologies. In detail, this is achieved by the definition of a unified *software architecture* and *software development methodology*, as well as by *standardised application interfaces*. By stressing the decoupling of hardware and software, the standard gives way to software reuse on different hardware platforms [18] [19], which is in compliance with the SoA design principles. Thus, many of the terms, treated within this thesis are influenced by the viewpoint of AUTOSAR.

Chapter 2

Methods

This chapter contains a definition of the most important terms related to SoA. Those terms include *system*, *component*, *service*, *architecture*, *service oriented architecture*, *dependability* and *functional safety*. Each of the following sections starts with an investigation and comparison of viewpoints from different sources. Subsequently, a definition, which is in accordance with the context of safety-critical embedded systems is presented in a bordered box. This definition is a combination of valid information from various sources as well as own findings. Most of the sections include also some additional information to the respective term.

2.1 System

In their GENESYS reference architecture Obermaisser and Kopetz describe a system as "an entity that is capable of interacting with its environment and is sensitive to the progression of time" [3, p.7]. The environment is thereby a system itself which produces input for other systems and acts according to their outputs. Which elements (cf. section 2.1.1) belong to the system, and which to the environment, is a matter of perspective.

Within the ISO 26262 standard, a system is referred to as a "set of elements that relates at least a sensor, a controller and an actuator with one another" [14]. This definition obviously explicitly refers to automotive because in other industry sectors a system does not necessarily contain actuators.

AUTOSAR, on the other hand, describes a system as "an integrated composite that consists of one or more of the processes, hardware, software, facilities and people, that provides a capability to satisfy a stated need or objective" [20].

Other typical characteristics are the presence of some kind of internal structure and the

hierarchical composition. Those are included in the resulting definition below.

A system is a hierarchical composed, time sensitive element, which interacts with the environment by processing input and providing output in turn.

It is concerned with satisfying a specific need or purpose and disposes of a more or less complex, internal structure which may include hardware, software and data.

For the scope of this thesis, the overall system is assumed to be a vehicle, if not stated otherwise. The environment therefore consists of other vehicles and the surrounding infrastructure. Nevertheless, the entire traffic could also be taken as a system and the environment would then be a different one.

2.1.1 System Element

In the ISO 26262 standard system elements are described as "system or part of system including components hardware, software, hardware parts, and software units" [14]. In general, system element is a very generic term and does not refer to any entities at a specific layer or with a specific characteristic. Instead, it can be more or less any entity of a system, since a system itself is defined as set of elements [14]. This is depicted in figure 2.1, which also shows the naming convention for other terms as it is used throughout this thesis.

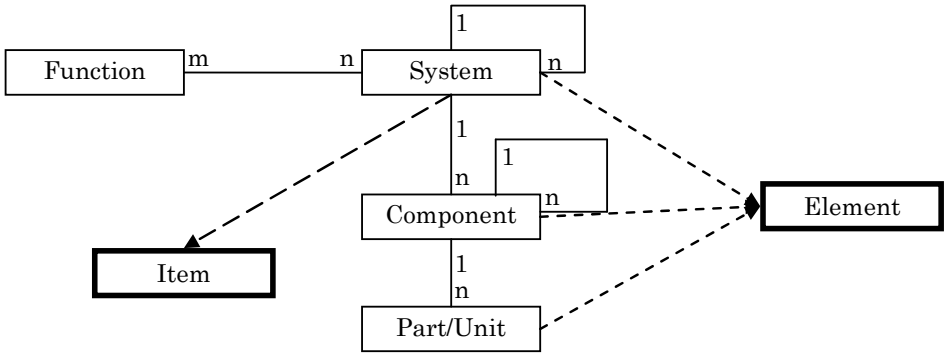

Figure 2.1: Relation of *system*, *component* and *element* according to ISO 26262 [1].

2.1.2 System of Systems

Systems are hierarchical and can be composed or decomposed into sets of interacting constituting systems. Often this is referred to by the term *System of Systems (SoS)* [3, p.7]. Thus, the SoS is in general the level above a given system and is therefore dependent on the definition of the related systems. SoSs may be geographically distributed and can become parts of other, bigger SoSs, when collaborating with other SoSs.

For a system vehicle, a SoS could be for example the traffic of a city, with many vehicles participating.

2.1.3 System Layers

The parts of a system can be divided into different layers of implementation. This kind of abstraction enables the comprehension of the overall relations. Unfortunately each field of research features its own, sometimes even contradicting, way of fractionising systems.

The GENESYS architecture by Obermaisser and Kopetz distinguishes between three different layers, denoted *chip-level*, *device-level* and *system-level* [3, p.44]. An example of the hardware elements at different levels by means of a system can be seen in figure 2.2.

System Level. The system level consists of devices which are themselves logically self-contained apparatus. With a vehicle as system this could be for example an ECU, a sensor, an actuator or the like [3, p.45].

Device Level. The devices at the system level contain a certain internal structures themselves. In terms of embedded systems those are in most cases chips [3, p.45], like the the AURIX^{TM} chip, which is frequently used in the automotive industry.

Chip Level. According to the implementation layers in the GENESYS architecture, the chip level is the lowest level of implementation. In case of an MPSoC (Multiprocessor System-on-Chip) this level contains the single IP Cores of the chip [3, p.46]

Another classification of layers is given by the Arrowhead Framework, which provides an hierarchy by means of documentation documents. Those are split into the three levels *system-of-systems*, *system* and *service* [21]. Their involved documents and relations are pictured in figure 2.3.

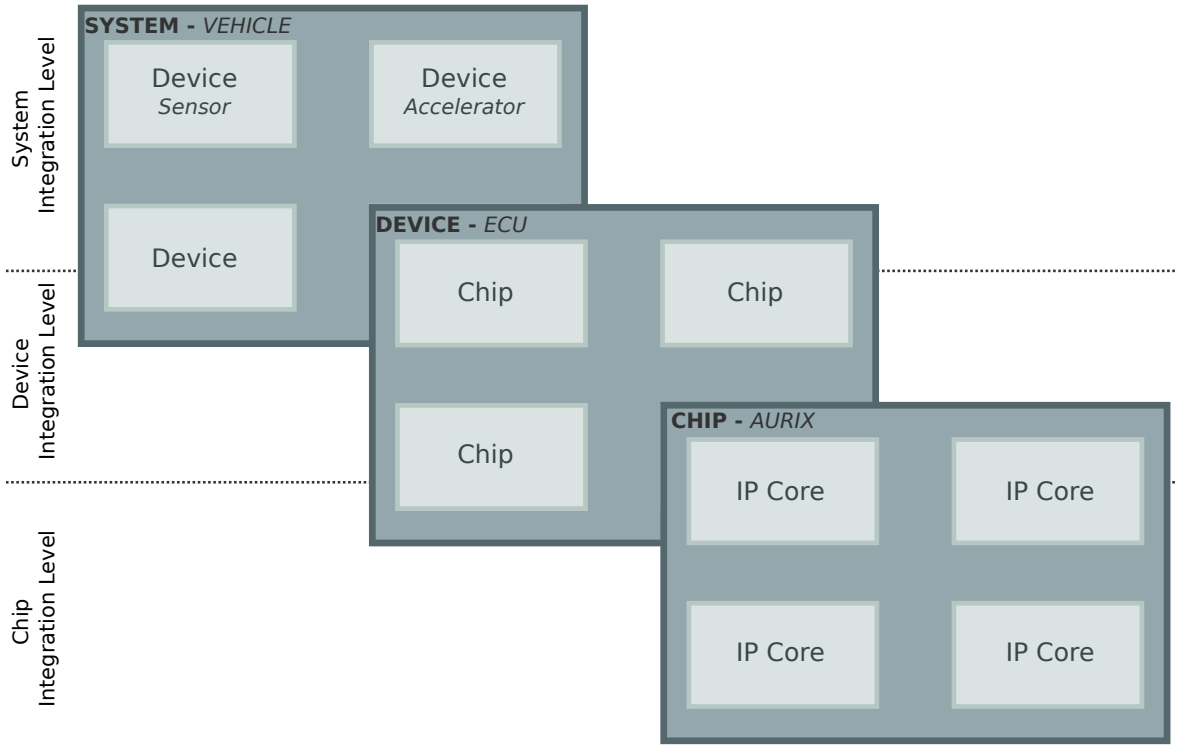

Figure 2.2: Hierarchy of the implementation layers of the system vehicle with examples.

System-of-systems. This level features the two documents *SoS Description (SoSD)* and *SoS Design Description (SoSDD)*. They differ in the amount of information they are revealing. While the first represents only an abstract view, the second also reveals the implementation of the SoS and its technologies [21].

System. The system level disposes of the two documents *System Description (SysD)* and *System Design Description (SysDD)*. Similarly, to the SoS level the first one features a kind of black box opacity and the second a white box view [21].

Service. The service level contains the four documents *Service Description (SD)*, *Interface Design Description (IDD)*, *Communication Profile (CP)* and *Semantic Profile (SP)*. The service description is referred to in section 2.3.2.

All these documents exist as templates which should be filled out during the development process of a system. They should feature a XML like style in order to be human and machine readable at the same time.

The fully developed systems can then be constituted to a SoS by an underlying cloud, as depicted in figure 2.4. All the system have specified and standardised interfaces and work together by means of three core services, denoted *Information Assurance*, *Information*

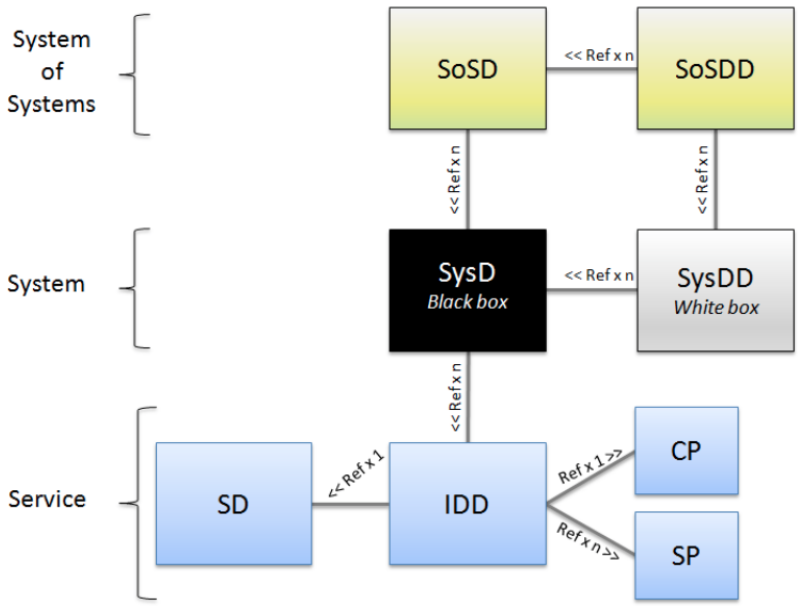

Figure 2.3: Relation of System, SoS and Service to one another [2].

Infrastructure and *System Management*.

Information Assurance (IA). This service is responsible for providing secure information exchange through authorization and authentication [2].

Information Infrastructure (II). The II service enables the listing of the services in the service repository (cf. section 2.5.2) and their discoverability [2].

System Management (SM). This is the core service for the SoS composition and features logging and monitoring abilities [2].

When comparing these two approaches by GENESYS and ARROWHEAD, it becomes obvious that the latter has a quite abstract point of view, which is biased towards SoA, while the approach by GENESYS is much more static and hardware oriented.

2.1.4 Embedded System

Embedded systems (ES) are computational modules integrated to physical devices and equipment. They have a predefined set of tasks and requirements and are capable of processing information [22] [23, p.xiii]. Compared to general-purpose computation systems ES usually dispose of less processing resources and come with narrower operation ranges. But at the same time they feature a high efficiency by optimally managing the available resources [24, p.283] [23, p.5]. Also, their presence is usually quite unobtrusive, because instead of mouse

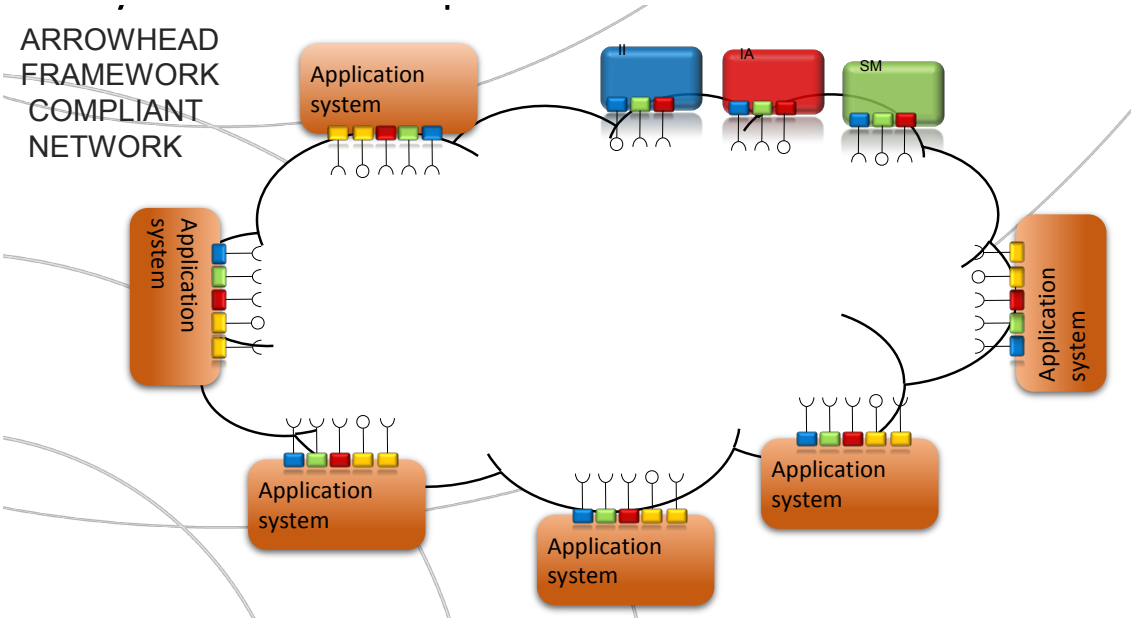

Figure 2.4: Implementation example of the Arrowhead framework [2].

and keyboard the user typical interface consists of input devices like buttons, steering wheels, or pedals.

ESs are reactive systems, which means that they perform a continuous interaction with the environment. The connection to the physical environment is realised by means of sensors, responsible for collecting information, and actuators for performing the actual reaction [23, p.8-9]. During operation, ESs are in a certain state and waiting for input. When provided with that, they perform computations and generate an output, which is handed back to the environment [23, p.9]. In safety-critical applications, issues like *time constraints*, *dependability* and *efficiency requirements* also have to be considered.

Time constraints. One challenge of ESs is the meeting of so called *time constraints*, which basically means the conduction of a computation within a given period of time [23, p.8-9] [22]. Kopetz [25] states "A time-constraint is called hard if not meeting that constraint could result in a catastrophe."

Dependability. ESs, operating in safety-critical environment like nuclear power plants, cars, trains or aircraft, must be *dependable*, for they are directly connected to the environment and have immediate impact on it. The dependability can be split up in further aspects, which are *reliability* (cf. section 2.6.1), *maintainability*, *availability* (cf. section 2.6.2), *safety* (cf. chapter 2.7) and *security* [23, p.4-5].

Efficiency requirements. Efficiency is a key concept of ESs and is concerned with provid-

ing a maximum computation performance while minimizing the required energy. The efficiency is measured in operations per Joule and has been been increasing almost exponentially over the last twenty years [23].

2.2 Component

The term component often appears in connection with SoA and frequently leads to confusion when it is put on a level with service (cf. chapter 2.3). This ambiguity is a result of the historic development of the SoA as successor of the component based software engineering (CBSE).

Obermaisser and Kopetz state that a component is a software or hardware unit that performs a specified computation within a given period of time [3, p.38] and communicates with other components by means of dedicated interfaces (cf. section 2.2.1). Like systems, components are hierarchical and therefore dependent on the point of view. Hence, a quantity of components may be seen as a single component from a different point of view. The ISO 26262 standard is in accordance with this definition and describes a component as "non-system level element that is logically and technically separable and is comprised of more than one hardware part or one or more software units" [14].

In contrast to that, a component is explicitly referred to as a piece of software by AUTOSAR:

> "Software-Components are architectural elements that provide and/or require interfaces and are connected to each other through the Virtual Function Bus to fulfill architectural responsibilities" [20].

Hence, a software component (SW-C) is an encapsulation of parts of the automotive functionality. There is no specific granularity dictated, meaning that an AUTOSAR software component might be either a "small, reusable piece of functionality (such as a filter) or a larger block encapsulating an entire subsystem" [26].

A component is a logical and technical separable hardware or software unit that is capable of performing a specific computation.

It offers an abstraction that simplifies the understanding of complex systems. Accordingly, components are hierarchical, meaning that they may be composed

to other, larger, components.

As suggested by this definition, the term component may be used for both, software and hardware. A component can be seen as black box, meaning that the more or less complex internal structure is invisible or of no concern for the user. Hence, other components stay unaffected from modifications of this internal structure, given that the behaviour at the *Linking Interface* (cf. section 2.2.1) remains unchanged [3, p.38-39] [4] [27]. As a self-contained subsystem, a component can be developed and tested independently and later be used as building block for systems or higher level components. In other words, the components can be described as the basic building blocks of a system [28].

Nevertheless, not everything is a component. According to Sametinger [27, p.2-3], an algorithm in a book is not a component, but it has to be implemented by means of an arbitrary programming language and equipped with well-defined interfaces in order to become a component.

2.2.1 Component Interfaces

The interfaces are necessary for any interaction with other system elements. Following the definition from Obermaisser and Kopetz, each component may dispose of up to four interfaces for communication with other entities. The *Linking Interface*, the *Local Interfaces* and the *Technology Independent-* or *Technology Dependent Interface*. They are illustrated in figure 2.5 [3, p.40-41].

Linking Interface (LIF). The LIF is a message based interface and responsible for offering the component's services. Its denotion is dependent on the level of integration, e.g. *Inter-IP Core LIF* at chip level or *Inter-Chip LIF* at device level. Nevertheless, the LIF is used only for communication to other components at the same layer and it is also the only place where a component may provide its services to other components [3, p.9].

The LIFs are always technology agnostic, which means that they do not expose details of the component's implementation or Local Interfaces. Accordingly, the implementation of the component can be modified, without other components noticing, as long as the specification at the LIF remains unchanged [3, p.9, 40-41].

Local Interface. The Local Interfaces establish the connection between a component and its local environment, which could consist of sensors, actuators and the like. If the environment is modified, the semantics and timing of the data should stay the same in order to not violate the specification. A Local Interface could also be mapped to a LIF of a component at the next-higher level. This is known *gateway component* and enables different layers to communicate with each other.

However, components do not necessarily require local interfaces. Such are denoted *Closed Components* [3, p.40-41].

Technology Independent Interface (TII). The TII is the instrument for configuring and reconfiguring a component, e.g. assigning a name, configuring input and output ports or monitoring the resource management. Starting, restarting and resetting the component is also executed through this interface. The TII communicates with the hardware, the operating system and the middleware, but not with the *application software (service)*, which is reserved for the LIF [3, p.40-41].

Technology Dependent Interface (TDI). The TDI enables a look inside the component and allows to inspect internal variables and processes. Thus, it is reserved for people who bring a deep understanding of the components internals and is of no relevance for the user of the LIF services [3, p.40-41].

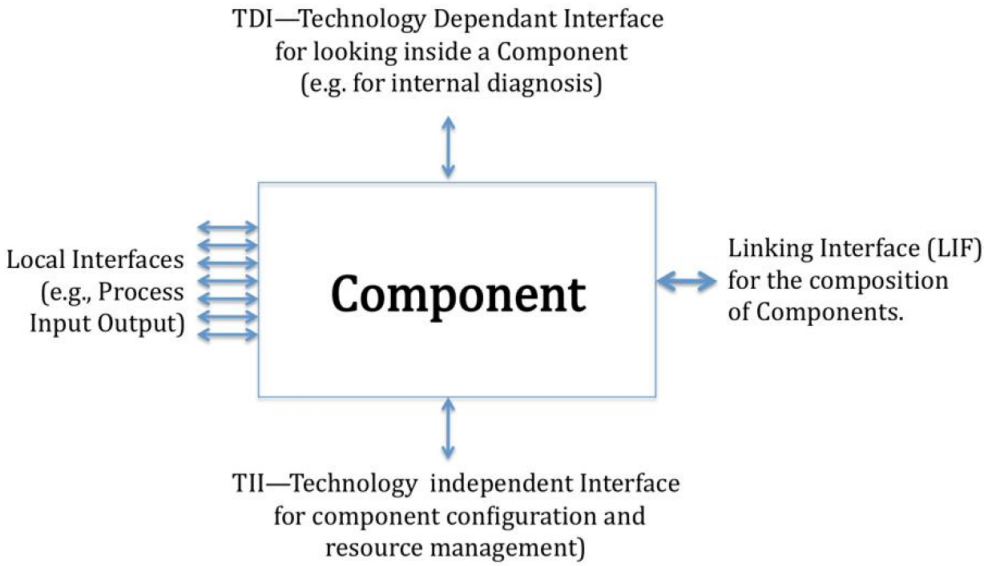

Figure 2.5: Interfaces of a component, with respect to the GENESYS architecture [3, p.40]

Compared to this rather implementation oriented point of view by GENESYS, the approach by AUTOSAR is much more abstract. According to their definition, a component may dispose

of a number of ports. A port belongs to one component only and is the interface a component uses to communicate with other components. Within this context, the term interface specifies a kind of contract or specification, on which services can be called at this port and the format of the data emitted at this port. There are four different types of interfaces, belonging to the two different communication patterns *Client-Server* and *Sender-Receiver* [4]:

Client-Server Communication. When this kind of communication is performed the *client-component* requests a specific service from the *server-component* and sends necessary parameters. The server then processes the incoming request and returns a response. Nevertheless, a single component can be a server and a client at the same time [4]. A schematic illustration of this type of communication is pictured in figure 2.6.

Sender-Receiver Communication. The *Sender-Receiver* approach is a bit different. The task of the sender is to distribute his information to one or more receivers, without ever getting a response in form of data or control flow. In fact, he does not even know the number or identity of the receivers. Those have to decide on themselves, how to deal with the received data (cf. figure 2.7) [4].

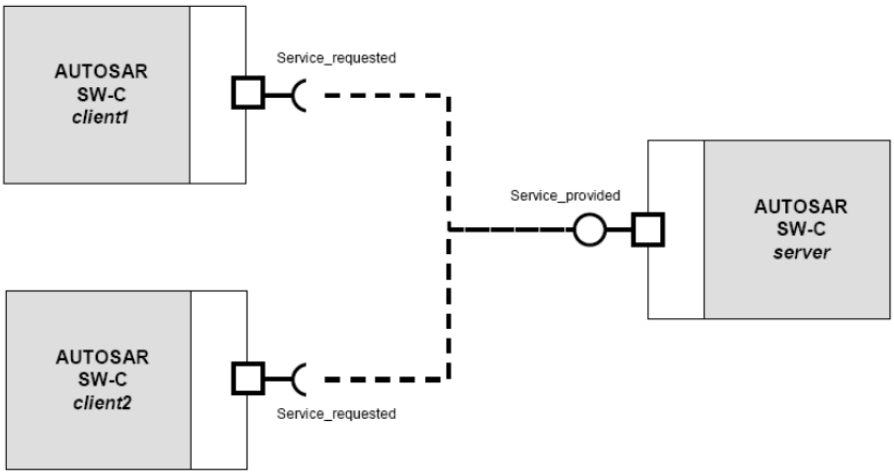

Figure 2.6: Illustration of the client-server communication [4].

2.3 Service

The perception of the term *service* is quite wide spread and influenced by a person's experience as well as the professional environment, e.g. the related research area. Hence, numerous different perceptions emerged, supporting various, even contradicting, views.

A quite generic definition of service is given by Arcitura [29]:

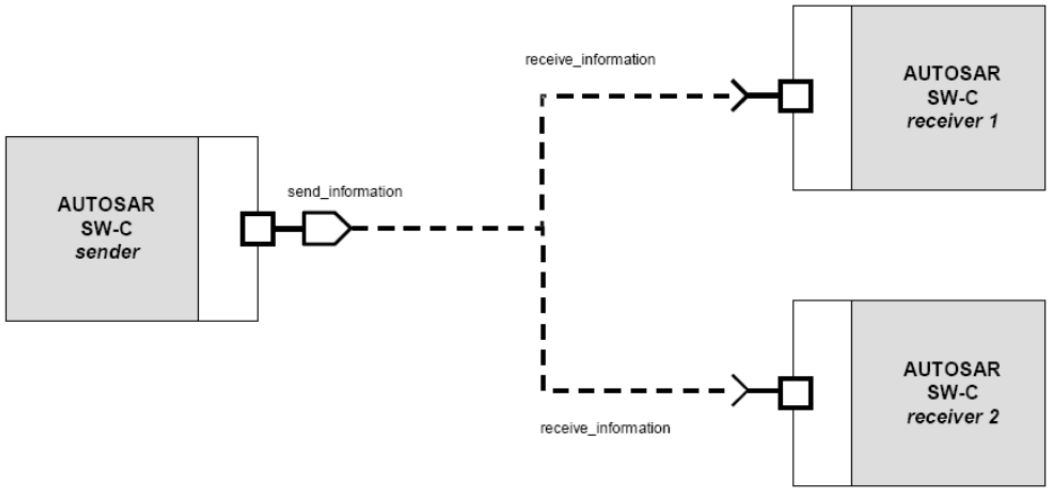

Figure 2.7: Illustration of the sender-receiver communication [4].

> "Each service is assigned its own distinct context and is comprised of a set of capabilities related to this context. Therefore, a service can be considered a container of capabilities associated with a common purpose (or functional context)."

The key information in this quote is that a service may offer multiple capabilities.

By Arrowhead a service is referred to as a part of a SoA [9]:

> "A service is the core building block of SOA, and is basically a software application performing some task, with a formal interface described using a standard description framework."

The definition by Obermaisser and Kopetz features a quite different point of view and describes a service by means of its surrounding environment [3, p.8]:

> "A service is what a system delivers to its environment according to the specification. Through its service, a system can support the environment, i.e., other systems that use the service."

What the specification of a service may look like is referred to in 2.3.2. While it is only indicated that a service interacts somehow with its environment, AUTOSAR gives a concrete answer to the question how this interaction is conducted [20]:

> "A service is a type of operation that has a published specification of interface and behaviour, involving a contract between the provider of the capability and the potential clients."

The terms *contract*, *provider* and *client*, which also appear in the definition below are investigated in detail in section 2.5.2.

As part of a system, a service is an independent logical unit with at least one capability and well defined interfaces, which have to be fully described by the service contract.

Services are the building blocks of a SoA and the containers for the functionalities a service provider offers to its consumers. In order to be applied in a service oriented architecture, a service must comply with certain key concepts.

2.3.1 Key Concepts of a Service

Erl et al. [30, p.27] state eight specific characteristics any service should posses. Those have been altered and extended with some attributes from other sources, resulting in the following listing with a total of nine characteristics. In some occasions there have been different nominations of equal characteristics. In those cases the alternative nominations are stated as well.

Opacity/ Encapsulation/ Abstraction. According to Erl [31, ch.8.1.], abstraction means to "hide information about a program not absolutely required for others to effectively use that program." Services hide an internal logic, which could be implemented by means of any suitable programming language or operating system. This allows the logic and implementation of the service to evolve over time, while still providing the functionality as it was originally published [31, ch.8.1].

From the service consumer's point of view the service appears as a black box, which does not impart anything of the underlying implementation or how the returned information is generated [32] [33] [9] [30, p.27]. This black box encapsulation disables any modification of the service by the user and is often referred to as *service interface level abstraction* [33].

Reusability. The idea of software reuse has been present since the early days of software engineering. In SoAs it is the key concept of a service and a necessary basis, as many of the other concepts would not even be possible without it [31, ch.9.1.] [30, p.27].

This design principle aims at making a service applicable for more than just one specific use case. Usually, it results in a more generic programming logic, which allows a wider range of application.

It should be noted, that the terms reusability and reuse are not equal. The former is the design principle, while the latter denotes the result which should be achieved by applying the concept of reusability.

Composability. Service are building blocks and thus existing services can be used in order to compose other, possibly more advanced, services through *service orchestration* or *service choreography*.

With orchestration, one service acts as a coordinator between all services involved, in contrast to choreography, where all composed services work independently with each other in a completely distributed manner [32] [9] [33] [30, p.27].

With respect to SoAs, the composing may take place at runtime [33].

Loose coupling. If two or more artefacts are somehow connected within a technical context, this is referred to by the term coupling. It indicates that two or more of "something" exist and is a measurement of the strength of their relationship, which is given by the amount of dependencies [31].

SoAs should feature a loose coupling, which means that dependencies should be reduced as far as possible [31]. This is achieved by using standardised interfaces, offering the service provider great flexibility in choosing design and deployment environment for offering their services [33] [9]. Well defined interfaces also allow a simple exchange of components by components from different vendors [11].

An example for this concept are web browsers. The service a web browser provides to the end user could be described as "interpret the HTML files and illustrate them in a user friendly way". No matter which web browser is used, the end result will stay almost unaffected thanks to the well specified applied protocols.

Discoverability. The concept of discoverability comes with certain requirements:

- Services have to constantly communicate the meta information they want to make public and all alternations,

- This information should be centrally stored and maintained in consistent format and
- The meta information must be accessible and searchable by those who want to use this resource [31, ch.12.].

The artefact that stores the service information in SoAs is the *service repository* (cf. section 2.5.2).

The discoverability of a service is not only critical during the runtime of a SoA, but also during the development process, where it provides answer to the question whether a certain functionality already exists or has to be built. Thereby, redundancies are reduced or prevented altogether [31, ch.12] [9] [33] [30, p.27].

Self-description. Service provider have to provide their clients with all the relevant information in form of a service description. This includes syntax, semantic and behaviour [33].

Statelessness. A state is referred to as the general condition of something. In computational systems a state can be represented by temporary data describing the state. SoA services are frequently required to hold a certain amount of state information through the lifespan of a service composition in order to fulfil their functionality [31, ch.11].

On the other hand, services can also be stateless; and in order to optimise reusability, services should aim at minimising their state information and their holding time for messages [33] [30, p.27].

Technology neutrality. Services should be independent from used technology in order to allow different platforms to use them [33].

This concept is questionable in connection with automotive, because in a car most of the implemented technology is given by certain standards and cannot be changed easily.

Standardised Service Contract. According to Erl [30, p.27], "Services within the same service inventory are in compliance with the same contract design standards." In other words, the service contract should be created by means of a given template, which is applied, at least, system-wide. The term *service inventory* is referred to in 2.5.2.

2.3.2 Structure of a Service

Concerning the structure, Krafzig [5, p.44] describes a service as it can be seen in figure 2.8 with the artefacts *service contract*, *interface*, *implementation*, *business logic* and *data*.

Service contract. *"A contract for a service (or a service contract) establishes the terms of engagement, providing technical constraints and requirements as well as any semantic information the service owner wishes to make public"* [31, ch.6.1].

The service contract is, more or less, the core part of every service, as it is the complete specification of the service between a provider and a consumer. It provides all the meta information concerning functionality, capabilities, expected behaviour, constraints, service owner, access rights, functional- and non functional qualities and information about intended performance and scalability of the service [5, p.44] [34, p.26] [33].

Physically, the service contract is represented by one or more *service description documents*, which should be human- and machine readable at the same time. In terms of web services the contract is usually represented by WSDL (Web Service Description Language) documents [30, p.43]. There is no dedicated language standard for automotive yet, but a XML based language like the WSDL would be an appropriate choice.

Erl [31] distinguishes between technical and non-technical service description documents. If a consumer connects to a provider, for example a database service, the technical contract could contain information like the database protocol and the query syntax or language, while the non-technical contract could contain related meta information like required safety measures or the physical location of the database [31, ch.6.1].

Interface. The interface is described in the service contract and specifies the access points and the functionalities of the service to the customers, which are connected via a network. A service may dispose of multiple interfaces [5, p.44] [33].

Implementation. The implementation is realised by programmes, configuration data and databases, which are necessary to provide the functionality specified in the contract. The term business logic in figure 2.8 is a bit misleading and should be seen as the algorithms encapsulated in the implementation [5, p.44].

Data. As stated in 2.3.1, a service may dispose of some state data for the time of its application. However, this is no necessary requirement for a service and the amount of stored data should be kept as low as possible [5, p.44].

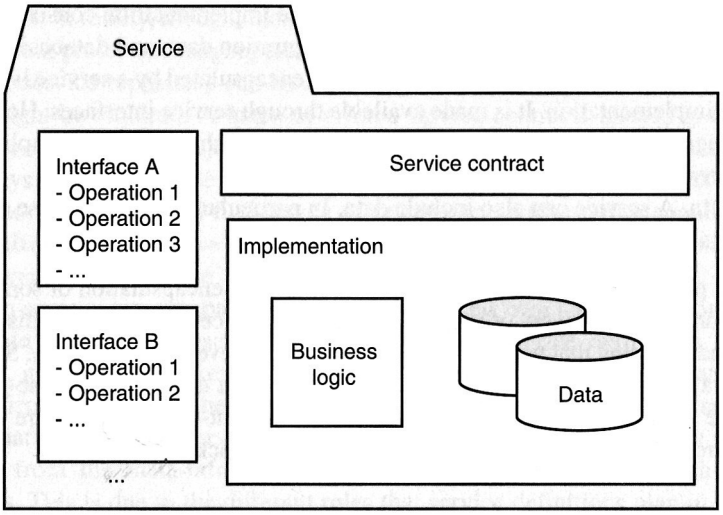

Figure 2.8: Structure of a service with the relations of the particular artefacts [5, p.45].

2.3.3 Services at Different Layers of Implementation

The system layers specified in 2.1.3 serve as basis for the assignment of services to different levels of implementation.

Chip Layer

The chip layer is the lowest layer of implementation and contains very generic services which are used by higher layers in order to create more advanced services. In various sources this layer is referred to as the core-, or platform layer. In accordance with that, the services at this layer are denoted *core services* [3, p.44].

Typical examples for services located at this level are message based communication services for the interaction of system elements, global time base services or mechanisms to compose the overall system out of the independently developed components. Such mechanisms include fault isolation services and clock synchronization services [3, p.7-12]. In other words, the chip layer provides a platform where recurring problems can be dealt with once and for all.

Device Layer

The device layer contains more advanced hardware parts. With respect to figure 2.9 these might be sensors, actuators, ADCs (Analog-to-digital converters), AURIX chips, the CAN (Controller Area Network) bus or a WDT (Watchdog Timer). Since there is no consistent denomination for the services located at this layer, they are referred to as *device services* within this thesis.

Device services make use of the underlying core services and other services at the device layer in order to provide their intended functionality. An acceleration sensor, for example, could make use of an ADC, which in turn operates with a platform service for the time for generating periodic sampling points.

System Layer

The highest layer is the system layer, containing the most advanced services, which are usually provided to the end user. Same as with the device services, there is no uniform denomination for services at this layer throughout literature. Thus, they are denoted *system services*.

System services emerge by binding together services of lower layers. An example for a system service could be a passive safety service for breaking or searing, which bases on an acceleration measurement service and other device services.

Figure 2.9 features an example of which hardware parts may belong to which integration layer with respect to a vehicle as considered the system.

2.4 Architecture

The term architecture is very generic and belongs to various different domains, like *hardware architecture*, *software architecture*, *system architecture* or *enterprise architecture*. In general, architecture is concerned with how the components of a system can be arranged and interrelated in order to assemble an overall system [7] [28].

Within the ISO/IEC/IEEE 42010 standard [7] the term architecture is referred to by "fundamental concepts or properties of a system in its environment embodied in its elements, relationships, and in the principles of its design and evolution." The *fundamental concepts* are thereby the *system elements* (cf. section 2.1.1), the *relations inside the system*, the *relations to the environment* and the *principles of design and evolution* [7].

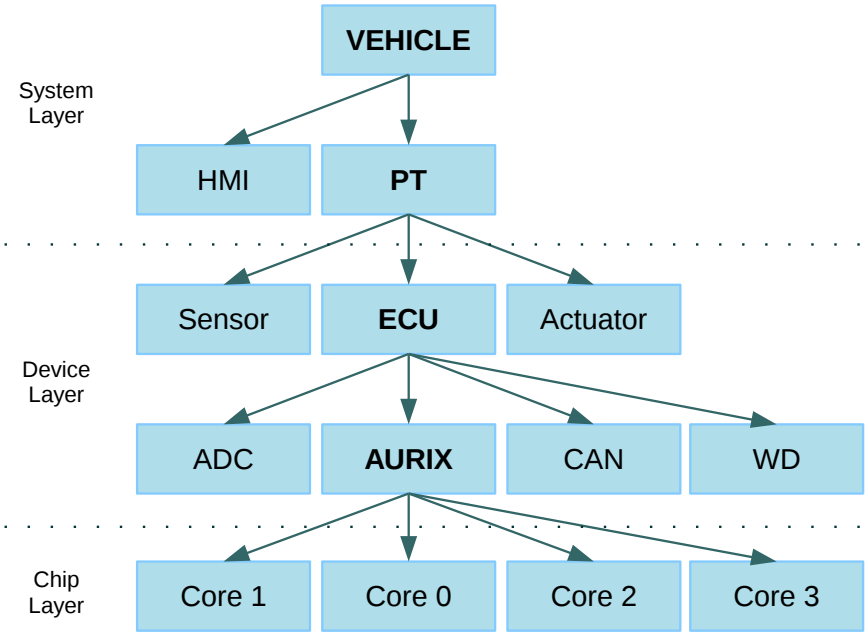

Figure 2.9: Examples of hardware parts at different levels [6]

This definition applies to any kind of architecture, but the emphases on these concepts vary with respect to the considered domain. The software architecture usually focuses very much on the system elements, while the enterprise architecture is more concerned with the principles of design and evolution [7].

This is in compliance with the definition of architecture by AUTOSAR [20]:

> "The fundamental organization of a system embodied in its components, their static and dynamic relationships to each other, and to the environment, and the principles guiding its design and evolution."

In [22] it is stated that the relationship and principles of design of the components, functions and the interface established between subsystems can also be defined by architecture.

The definition presented below is compatible with all kinds of architecture design, for they share the same basic principles.

An architecture is a systematic description of the structure of a system by means of its involved components and their relations to each other, and specifies also the connections and interactions of a system to its environment.

At the same time, architecture is also responsible for determining the principles of design and evolution.

2.4.1 Demarcation from Related Terms

The placement of architecture in relation to other entities like system or environment is illustrated in figure 2.10.

Architecture description. Many sources mix up the definitions of *architecture* and *architecture description*, which is a recurring source of confusion. In contrast to the actual architecture of a system, the term architecture description denotes the artefacts which document the respective architecture [7].

According to the ISO/IEC/IEEE 42010 standard, the architecture description is used to express the architecture of a system of interest by means of the following elements:

- Specification of the purposes of the system,
- Suitability for achieving these purposes,
- Feasibility of construction and applicability,
- Maintainability,
- Evolvability and
- Association of these concerns with the stakeholders having these concerns [7].

One and the same architecture can be described by several different architecture descriptions, and at the same time, an architecture description can also characterise multiple architectures [7].

Stakeholder. The stakeholders are all people which are somehow related to the system and have any interest in the system. Those include users, operators, owners, developers, maintainers and others [7].

System concern. A specific system concern can be held by one more stakeholders and can appear in various different forms, e.g. expectations, responsibilities, requirements, assumptions, dependencies and more [7].

Purpose. Purposes are one kind of system concerns, which are issued by the stakeholders [7].

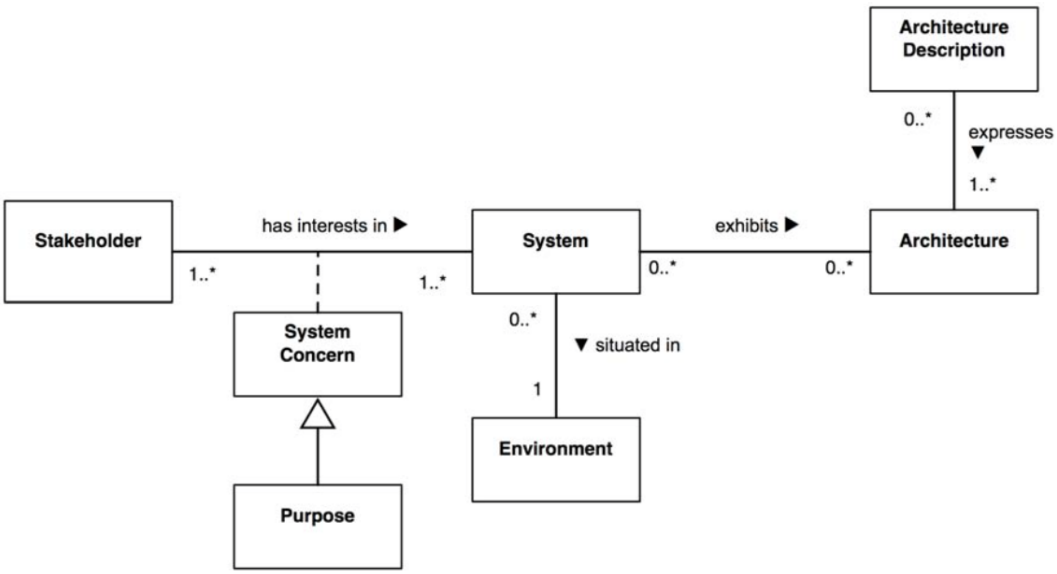

Figure 2.10: Relations of architecture to other entities [7]

2.5 Service Oriented Architecture

The term service oriented architecture has been widely used for marketing and praising new products. This resulted in various misinterpretations of the term, because some vendors suggested that a SoA is something that can be bought or installed on an existing system, missing the point that SoA was not a product, but a set of design paradigms that can be applied on architectures.

The driving factor for the application of this design paradigm are certain benefits that come with the modularisation of software. Those are not only reduction of development costs, but, with respect to embedded systems, also a saving in hardware components and complexity [12]. Furthermore, it increases flexibility, scalability and fault tolerance [35, p.33] [34, p.17-18].

Different authors and companies explain the term from different viewpoints and with different focuses.

OASIS. OASIS is a non-profit consortium that drives the development, convergence and adoption of open standards for the global information society.

> *"A paradigm for organizing distributed capabilities that may be under the control of different ownership domains. It provides a uniform means to offer, discover, interact with and use capabilities to produce desired effects consistent with measurable preconditions and expectations"* [36].

Papazoglou. *"Service-oriented architectures (SOA) is an emerging approach that addresses the requirements of loosely coupled, standards-based, and protocol independent distributed computing"* [37].

Donini, Marrone et al. *"SOA is an architectural style for building software applications that use services available in a network such as the web and it represents the widest accepted model to design geographical distributed systems"* [38].

Arcitura. *"Service-oriented architecture is a technology architectural model for service-oriented solutions with distinct characteristics in support of realizing service-orientation and the strategic goals associated with service-oriented computing"* [29].

The definition presented below has emerged as result of extensive investigations and reviewing numerous sources. In contrast to all the other definitions, which are somehow biased due to their relation to a certain research area, this one is quite generic and may be used for any kind of SoA. In case of embedded- or safety-critical systems, there are of course additional characteristics which are crucial.

The service oriented architecture is no actual design, which can be simply implemented or installed, but a collection of design principles for distributed systems.

Originating from the object oriented- and component based engineering, it pushes the concept of software reuse to a new level by using technology independent and loosely coupled services.

Accordingly, a SoA disposes of an arbitrary number of services, which are interconnected by means of an underlying network with predefined protocols.

As stated, SoA is no specific implementation but a set of rules to achieve a certain target state. The final implementation can therefore consist of multiple technologies, products, APIs (Application Programmers Interfaces) and supporting infrastructures [30, p.29]. This enables an unproblematic exchange of components by components of other vendors, as long as the provided services remain unaffected.

Nevertheless, a SoA is not just a simple collection of services, but offers also composition mechanisms for services, enabling the creation of agile, higher-level services with a more sophisticated functionality, without having to build everything from scratch. [34, p.12].

2.5.1 Historic Development

The term *Service oriented Architecture* first appeared in 1996 [35, p.7]. It emerged from the CBSE (cf. figure 2.11) and was more or less an improvement, for it allowed the components to be wider distributed and looser coupled. However, since both approaches feature certain advantages, both of them have been developed in parallel ever since, resulting in many similarities, but also many differences [33].

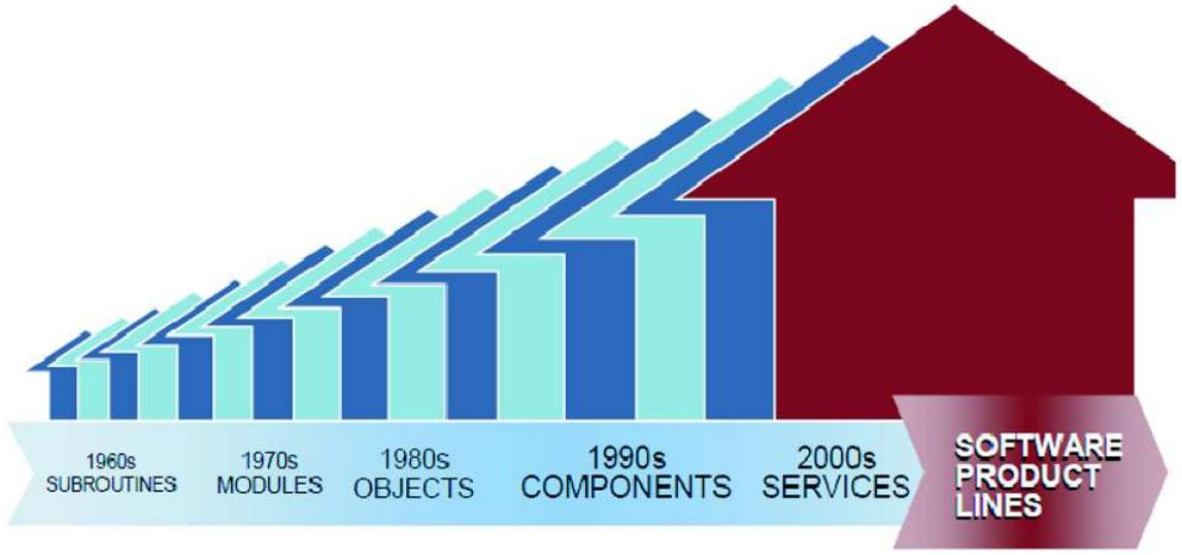

Figure 2.11: Development of software reuse concepts from the 1960 to present [8].

2.5.2 Structure of a SoA

The four main artefacts of a SoA are *service provider*, *service consumer*, *service repository* and the *service contract* [9] [33] [22]. There are also alternative terms for those, which are mentioned here; but throughout the remain of this thesis the previously stated terms will be used.

Service provider/ Service Owner. The task of the service provider is to provide a service and its functionality. Additionally, he should formulate the service description in form of a contract, which is then handed over to the service repository in order to make the service discoverable [33].

Service Repository/ Service Registry/ Service Directory. The service repository is, more or less, a database of services which may be physically distributed. It disposes of certain publishing mechanisms in order to make services discoverable by the service consumer. Therefore it contains all the information of every version of the service, as well as meta information like physical location, provider information, technical constraints, security issues, and, of course, the link to the registered service [5, p.60-61] [33] [39].

Services can be added to, or taken from the service repository dynamically. Thus, services need to be already running and ready to use in order to be discovered and composed at runtime.

Service Consumer/ Service Client/ Service Requester. The service consumer is the instance that calls the service and can be either an end-user or another service. He sends a request for searching the service repository for specific services by means of the service interface description. Subsequently, the repository returns a list with suitable services. If an appropriate service is identified the service consumer creates a dynamic binding with the service provider in order to invoke the service and interact with it [33]. This procedure is depicted in figure 2.13.

Service Contract. The service contract is described in detail in section 2.3.2. It is handed over to the service repository from the service provider.

Service Inventory. Erl et al. [30, p.41] mention this additional term in connection with SoA. According to their definition, "A service inventory is an independently standardized and governed collection of complementary services within a boundary that represents an enterprise or a meaningful segment of an enterprise."

The term enterprise in this definition appears a bit bizarre and is a result of the research area related with this source. For the scope of this thesis the boundary is defined as a vehicle. Hence, the service inventory includes all services which could be provided by the vehicle itself. The difference to the service repository is that the service does not need to be available, or even implemented. Instead, it is a static list of developed or conceived services.

The relations of the various artefacts are depicted in figure 2.12.

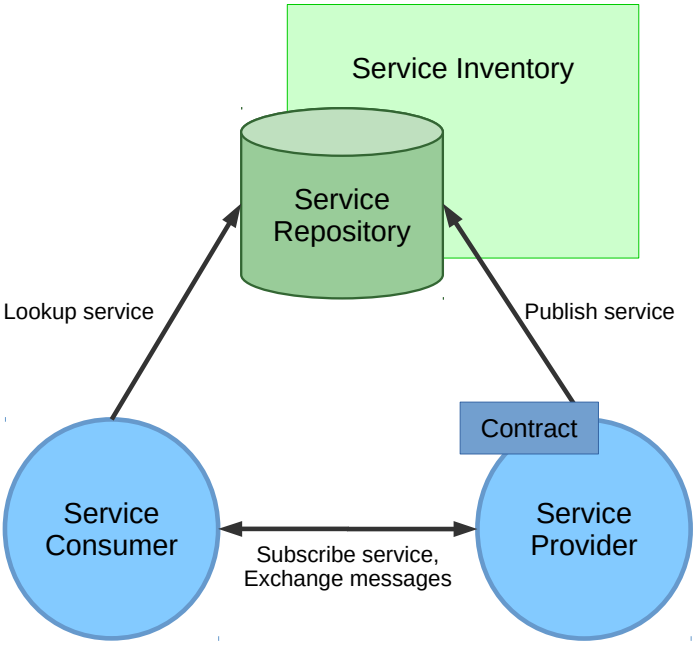

Figure 2.12: Relation of *service provider*, *service consumer* and *service repository* [9]

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2.6 Dependability

The terms availability and reliability, which can be found at any level of implementation, are closely tied, and usually appear together. Often, they are coupled with the term maintenance, which also plays an important role in the design of any system [3, p.116] [40].

2.6.1 Reliability

Reliability denotes the time an element needs to fail while it is operating. In other words, it is "the probability of the failure-free operation of a system for a specific period of time in a specific environment" [3, p.116]. Nelson [41] describes it more technically as "Reliability, $R(t)$, is the conditional probability that a system can perform its designed function at time t, given that it was operable at time $t = 0$."

In terms of services, the reliability can be enhanced by the ability to recover state information after an interruption and continue the service like it has never been interrupted [3]. The reliability of higher level elements is of course dictated and limited by the reliability of its sub elements.

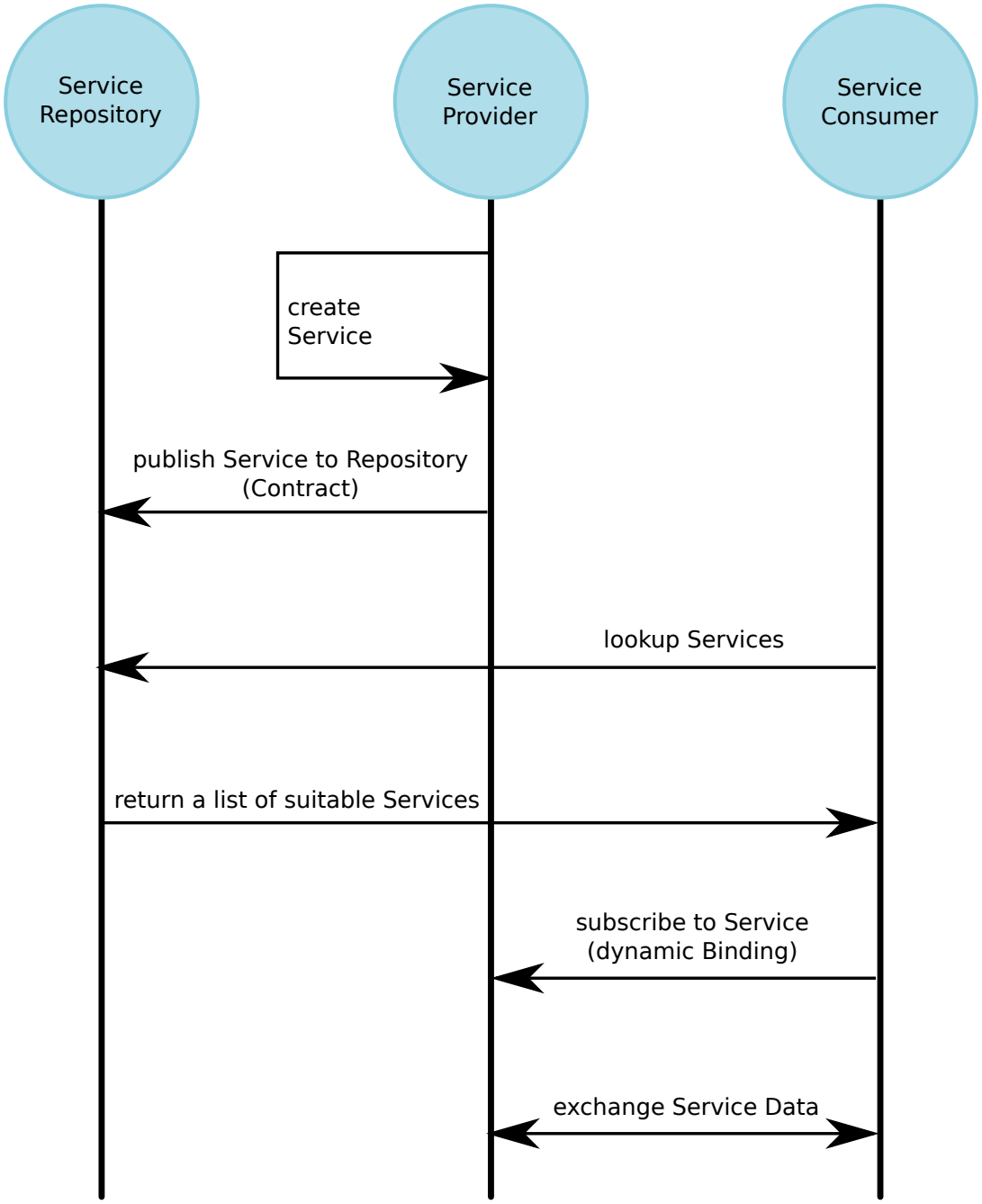

Figure 2.13: Chronology of binding a service in a SoA.

2.6.2 Availability

The definition of availability is ambiguous. The ISO 26262 standard defines the availability as the "capability of a product to be in a state to execute the function required under given conditions, at a certain time or a given period, supposing the required external resources are available" [14]. Obermaisser and Kopetz, however, describe it as the "probability of a software service or system being available when needed" [3, p.116], which is quite similar to the definition stated in [40] and [41].

The difference here is that the prior denotes availability as the availability of an element at this very moment, while the latter defines it as a probability of an element to be operational and ready to use.

Two important terms which come in connection with availability are MTTF (Mean Time To Failure), the expected time until the system fails, and MTTR (Mean Time To Repair), the necessary time to restore a failed system to normal operation. The availability A can therefore be expressed as $A = MTTF/(MTTF + MTTR)$ [41].

The availability characteristics of a system are represented by its reliability and maintainability. Accordingly, even highly reliable entities can have a poor availability if the repair time of its sub entities takes very long [40]. The application of dedicated *fault tolerance mechanisms* (cf. section 2.8) can improve the availability [41].

2.7 Functional Safety

The term safety denotes the absence of an unreasonable risk [14]. Systems which interact with people, and could endanger those in case of a malfunction, have certain safety requirements in addition to functional requirements. Those safety requirements are issued by dedicated standards like the ISO 26262 standard. In accordance with that, the ISO 26262 standard describes functional safety as the "absence of unreasonable risk due to hazards caused by malfunctioning behaviour of E/E systems" [14]. Risk, in turn, is defined as the product of the *probability of occurrence* and the *severity of harm* [14].

In contrast to security, functional safety only addresses the absence of risk due to equipment malfunction. It does not care about possible risks due to malicious events caused by other people, or just inappropriate operation of the user.

2.7.1 Disambiguation Safety and Security

Two terms which often appear together and appear very much alike are *safety* and *security*. Nevertheless, they have a completely different meaning in technical systems.

The term *safety* denotes the "absence of an unreasonable risk" [20] [14] and is concerned with correct operation of the equipment in a specific system and environment. Therefore, it is concerned with things like *error detection*, *fault prevention*, *failure migration*, *diagnosis* and similar.

Security is concerned with preventing unauthorized access, or unexpected input. AUTOSAR defines the term as "Protection of data, software entities or resources from accidental or malicious acts" [20]. With the advance of software and interconnection in vehicles, security becomes more and more of an issue because all the functionality in a car, even highly critical ones like an automatic brake system or a collision warning system, will be approachable through a network. Especially if the vehicle gets connected to any proprietary and publicly accessible network like the Internet. With the advance of the SoA paradigm for automotive, it is planed to run remote diagnosis and firmware updates wireless. This is an obvious weak point and an exploit of this can affect the operation of the vehicle and the safety of the driver [42].

Although safety and security are separate disciplines, the functionalities of a vehicle cannot be classified into safety or security relevant functionality, but always include aspects of both disciplines at the same time [42].

This thesis is mostly concerned with the safety-oriented point of view.

2.7.2 Safety Related Terminology

Fault, *error* and *failure* are terms which are often mixed up and used in the same context, since they seem to be very similar in their meaning. Nevertheless, their disambiguation is crucial for some of the following sections.

Fault. In ISO 26262 standard a fault is listed as an "abnormal condition that can cause an element or an item to fail" [14] [20].

Faults come in different forms. An *intermittent fault* occurs from time to time and disappears without any repair measures having taken place. This is typical for hardware components which are worn out and almost breaking down. *Transient faults*, on the other hand, appear once and do not recur afterwards. This is for example the case if

there is some electromagnetic interference. *Permanent faults* naturally remain until the faulty component is exchanged or repaired [14].

A term related to fault is *fault coverage*. It denotes the number of the faults detected as a percentage of the total number of faults affecting the system [10].

Error. An error is the deviation of a computed, observed or measured value or condition to the expected, theoretically correct value. An error occurs as consequence of an unexpected operating condition or a fault. Nevertheless, a fault does not necessarily lead to an error [14] [41] [20]. If the error exceeds a certain threshold it can cause a failure [20].

There are two different classifications of errors, as they can be divided either into *soft-* and *hard errors* or *data-* and *control flow errors* [43] [10].

Soft Error. Soft errors occur when a temporary extra charge is induced into the electric circuit. Usually this is due to cosmic radiation and causes a flip of the data state in a memory element [43] [10].

This kind of error will become even more severe in the future, due to the decreasing size of electronic circuits, as well as their increasing complexity [10].

Hard Error. In contrast to soft errors, hard errors are caused by a constant property change of an electric component. This could happen either because of a change in the input temperature, or input voltage [43].

Data Error. A data error denotes a change of the data stored at any memory location or register [10].

Control Flow Error. A control flow error leads to wrong execution sequence of instructions. This is the case if the memory storing the address of the next execution instruction is changed [10].

Failure. Failure denotes that an element is not able to provide its functionality any longer. This happens usually due to errors in the element or the environment, which are in turn caused by various faults [14] [41] [20].

The averaged frequency of occurrence of a failure is denoted *failure rate*. It is counted in *hours of operation until a serious fault*, e.g. 10e5 to 10e9 hours of operation [22].

Another term which frequently comes up in connection with failure, is *failure mode*. This denotes, depending on the consulted source, either the manner in which the component fails [44], or the manner by which an occurred fault is observed [45].

2.8 Fault Tolerance

The key concept of a *fault tolerant* design is to enable a system to provide its intended functionality in the presence of a given number of faults [41].

Thus, the fault tolerance mechanisms are not responsible for preventing the occurrence of faults, but assure that a fault does not directly lead to the violation of the safety goals which maintain the system in a safe state [14]. Possible faults include not only internal faults like design-faults or hardware wear-outs, but also external ones; for example misuse by the user or cosmic radiation. Fault tolerance mechanisms have become indispensable for advanced electric systems because due to the billions of transistors present and the various circumstances, which can lead to faults, faultless systems remain an utopian dream [3].

2.8.1 Design of Fault Tolerant Systems

The prerequisite for designing a fault tolerant system is a so called *fault hypothesis*, which is an assumption regarding the type and frequency of faults the system is supposed to handle.

These can include

- *Software error* - Especially for complex software it can be assumed that there are a certain amount of bugs and imprecisions.
- *Delay and disruption error* - This is relevant for all networking systems.
- *Transient faults* - This means a possible corruption of Flip-Flops or memory cells with the progression of time.

2.8.2 Fault Tolerance Strategies

There are various different approaches in order to make a system fault tolerant. They are described in more detail in the following.

Error Detection. The detection of errors is usually done by comparing the results of redundant elements [41].

Error Masking. This denotes the dynamic correction of generated errors at runtime and requires multiple redundant systems and voting systems in order to do that [41]. An example of an error masking mechanism, which is also provided by the GENESYS architecture, is *TRM* (Triple Modular Redundancy). With this method three independent components execute the same function. The output is then processed by a majority-voting system in order to produce a single output. If any of the three systems fail, the other two are able to correct and mask the fault - From the outside it is not even visible that a fault occurred [46].

Error Containment. Error containment is supposed to prevent the propagation of an error across specified regions. Those are denoted *Error Containment Regions (ECR)*.

Diagnosis. This is used for identification of a faulty element, which is responsible for an error [41]. This can be conducted by redundant elements whose output is compared by a voting system.

Repair/ reconfiguration. Although repair and reconfiguration obviously leads to the elimination of an fault, its affiliation to fault tolerance mechanisms is questionable, as it usually means an interruption of the operating system. However, advanced systems may also dispose of various functions which are able to repair and reconfigure faulty parts at runtime by restarting parts, or other countermeasures.

Recovery. Recovery is the return of a system to a state, where it able to operate according to its specification [41].

Chapter 3

Results

This chapter deepens and extends some of the terms given in chapter 2 and investigates them with respect to automotive. The chapter is structured into five main section, entitled *SoA in embedded systems (Embedded SoA)*, *SoA in automotive*, *safety services*, *service development process* and *use case scenario*.

The first section extensively deals with the application of the service oriented design paradigm in embedded systems and highlights the challenges this approach has to face when it has to face certain safety requirements. Moreover, the differences to "conventional SoAs" as web application is investigated in detail. In the second section various examples of services relevant for functional safety are described in detail, and their intended functionality, as well as possible implementations in terms of architecture is presented. The final part consists of a simplified use case, dealing with the design of an *error detection service* with respect to the design phases *service investigation/ planning*, *service inventory analysis*, *service oriented analysis* and *service oriented design*.

Most of the findings and concepts in this chapter are (not yet) covered in literature, but are the result of numerous meetings and discussions at **VIRTUAL VEHICLE Research Center** during April to July 2015.

3.1 SoA in Embedded Systems (Embedded SoA)

The service oriented design paradigm was originally designed for the application on the Internet, which offered ideal prerequisites for this kind of architectural style. An underlying network for interconnection already existed and time constraints are of no concern, as delays are unlikely to cause a disaster. Thus, it is no surprise that web services are the application

area, where SoA has scored the highest market penetration [22] [13].

3.1.1 Drawbacks in Embedded Systems

In contrast to web services, ESs consist of numerous interconnected nodes with diverse measurement-, steering-, or computation capabilities. Accordingly, they have to face additional challenges like *limited resources*, *different complexity of hardware*, *time constraints* and others [11] [12]:

Limited resources. One obvious major drawback of ESs are the quite limited resources which are designed for highly specialized purposes and lack computation power as well as storage capacities [22] [11] [12].

Different levels of complexity. The complexity of hardware in ESs varies greatly. The implemented components may include very primitive sensors with few capabilities, but also very advanced nodes like MPSoCs [11] [12]. In other words, there are high level *information systems services*, as well as low level generic *embedded system services*. A SoA has to deal with the connection and integration of them [22]. This task gets aggravated if SoAs in ESs become interconnected with high level SoAs like web applications.

Event- and data-driven. In contrast to web services, an ES disposes of a network with (many) sensors. Thus, the ad-hoc *request-response* message pattern, which is common for web services, cannot be simple adopted for the *event- and data driven* ES [12].

Instead, the communication in those is conducted mainly by a *fire and forget* scheme: A sensor measures some data and publishes it to all connected services, which have to decide on themselves whether the received data is relevant and how to process the received information [12].

Lifespan of services. Another difference to web services is the lifespan of services. While web services are used to work only a limited number of hours (or even just minutes), the services in ESs could have application times of multiple years, or may even last for the lifespan of the system [13].

Dynamic character. The components of a SoA show dynamic characteristics: "new nodes may enter the network, existing nodes may fail and network characteristics can change over time, especially if wireless communication media are used" [12]. This could become

an issue, as the set of implemented components in an ES is usually determined at assembly time.

Time constraints. ESs are *time-critical*, meaning that computation must be conducted within a given time window in order to allow the correct operation of the system. Especially in a safety-critical system like a vehicle, which is used to operate at high velocities, a violation of those time constraints could cause serious incidents.

These obstacles are the reason why web services and safety-critical embedded systems are often considered as non-related areas [22]. Nevertheless, Sommer et al. mention various benefits which come with the application of the SoA design philosophy in ESs:

- Decoupling configuration from environment,
- Improvement of reusability,
- Improvement of maintainability,
- Higher level of abstraction,
- Enhanced interoperability and
- More interactive interfaces between devices and information system [13].

To sum up, the SoA paradigm has to overcome many serious drawbacks if applied in ESs, but at the same time it offers numerous advantages and possibilities, which are just not possible with current systems.

3.1.2 Embedded SoA

There is no uniform denomination for SoAs in ESs throughout literature. Thus, it is referred to by the term *Embedded SoA* (abbreviated as ESoA) for the scope of this thesis.

The following definition is the result of intense investigation in this area and extends the definition from section 2.5:

The Embedded SoA works at a lower, very hardware oriented level, with a predefined and unchanging set of component.

The conventional SoA is located above the embedded SoA and connected through various interfaces.

With respect to the example of a vehicle, the ESoA operates on elements like the power train, various devices (sensors, actuators, controllers, etc.), while the SoA level contains the vehicle as overall system. With other vehicles and environmental components it may form a SoS.

Regarding the ISO 26262 standard, the requirements for ESoA can be related to **Part 3: Concept phase**, and the SoA to **Part 4: Product development at the system level** as depicted in figure 3.1.

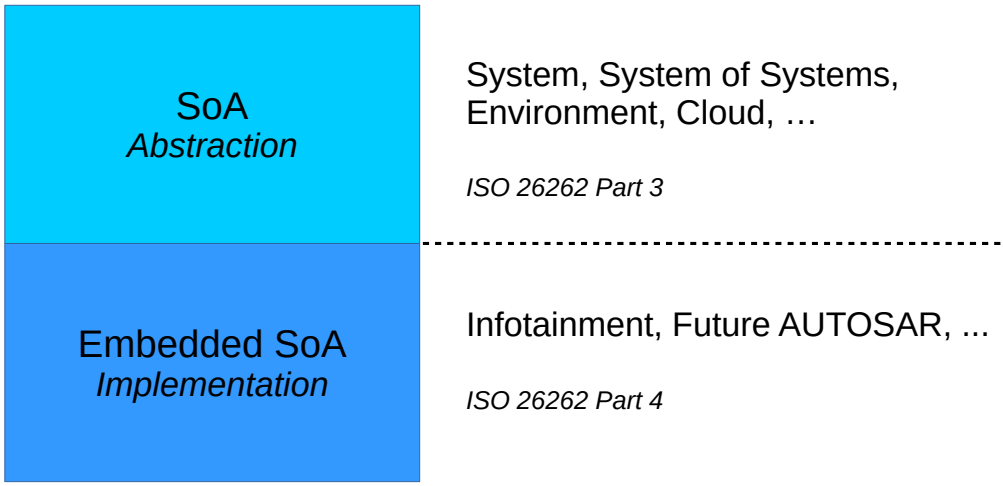

Figure 3.1: Relation of conventional SoA to Embedded SoA.

3.2 SoA in Automotive

In the future of automotive all vehicles will, most likely, be interconnected with each other and also with the environment. This is a necessary prerequisite for acting autonomously, e.g. detecting whether the traffic lights at a crossing are green. Within this document those futuristic vehicles are referred to as *connected cars*.

The opportunities and advantages of the SoA approach are described extensively in 3.1 and 2.5. In terms of vehicles, the major advantage would be the possibility to reduce the quantity of computation hardware. At present time, each component disposes of his own dedicated hardware for conducting computations. Although it is unused for the majority of time, it comes with a lot of extra weight, which is a major violation of the guideline stated in [23, p.7], "Embedded systems should exploit the available hardware architecture as much as possible." The SoA approach might not only reduce the weight, but thereby also the complexity and

costs of the overall vehicle. In today's automotive systems it is common practice that each vendor uses his own proprietary network and additional hardware, prohibiting the application of hardware components from another vendor [12].

However, there are some obstacles which prevent the application of the SoA paradigm in vehicles right now. On the one hand, those are the strict regulations in connection with safety critical real-time systems like vehicles [47] - with respect to automotive there are not even regulations, addressing SoA, yet - on the other hand, there are pure technical constraints. The AUTOSAR architecture, which is widely applied today, is not constructed for dynamic reconfiguration or binding of services at runtime, but everything has to be specified at building time. Nevertheless, there is already an approach by AUTOSAR, denoted *Future AUTOSAR*, dealing with this very issue. Unfortunately, the actual implementation in mass produced vehicles lies in the distant future.

To sum up, it might take some time before the design paradigm will be used for the lower, hardware-oriented layers of the ESoA. Instead, it would be a promising approach for higher layers like the SoS. The vehicle as system could offer certain services to its environment and the other way round. A good example, which has been mentioned before, are traffic lights. If the the traffic lights in Germany use another service as the ones in Austria, a SoA could enable the dynamical binding of the new service, when a vehicle approaches the border.

3.2.1 Location of the Service Repository

The description of the term service repository is covered in 2.5.2. Nevertheless, questions arose concerning its location and actual implementation with respect to automotive. This section covers the findings concerning this matter.

For SoAs in automotive it is very likely that there will emerge various, physically and logically distributed repositories. One repository inside of every vehicle, containing all the services provided by the vehicle itself and used by the vehicle itself. This repository obviously has to be located inside the vehicle, for it has to be also available when the vehicle is operating in urban regions or when it is just not able to connect to its environment. These repositories may be referred to as *local service repositories*. Examples for services in this repository are services which are closely connected to hardware components like sensor measurements or communication services, but also safety services for fault- and error detection, which need to be available whenever the vehicle is operated.

The counterpart to the local service repository is denoted *external service repository*. This

could also be physically distributed on various server clusters and should hold mostly services which are needed for interacting with the environment. To connected cars it could provide all the services needed for managing the traffic. In order to stick to the previous example, a service at this repository could be dedicated to managing the traffic lights of a particular city or zone. If it is bound by a vehicle operating in this zone, it should then be able to decide automatically, whether it has to stop at an intersection.

Other services which could be located in this repository are *update services*. If an update for an existing service in the local repository is available, the vehicle could detect this automatically and subsequently load and install the service in question.

3.2.2 Service Contract

The service contract (cf. section 2.3.2) is the complete and extensive description of the service and with respect to automotive it should also contain documentation from AUTOSAR, the ISO 26262 standard and documentation regarding functional safety. One of the goals of **Work Package 1** of the EMC2 project to extend the service contract by a functional safety part.

At the beginning of a service development process, the contract exists just as an empty template, which gets filled more and more as the development advances. A template which should be used for the development of services in the automotive industry is provided by the Arrowhead project.

3.3 Safety Services

For most safety-critical ESs security is also an important issue. Accordingly, most of the provided services must be fault tolerant and secure at the same time.

Functional safety is directly related to availability (cf. section 2.6.2) and thus the overall safety can be increased by increasing the availability [48]. The availability, in turn, can be increased by services for failure detection, error detection and error masking, which also enable recovery from errors.

In the following sections, the interference and connection of safety and security services is analysed, before the functional principles of a few selected safety services is presented in detail.

3.3.1 Relation of Safety and Security Services

In vehicles it is not really possible to distinguish safety functions from "normal" functions, because a malfunction in any functionality could lead to a disaster [49]. Accordingly, all services are also considered to be safety-critical.

Since future vehicles are planed to be always connected to the outside world, security must also be taken into account, because a malicious attack on the system could be equally disastrous. In terms of security, there will be dedicated services which take care of authentication, permission management and comparable functionalities.

Most of those safety- and security services cannot be assigned entirely to one discipline, but have overlapping responsibilities, as depicted in figure 3.2. According to various findings, this effects especially the services for *authentication*, *memory protection* and *failure detection*.

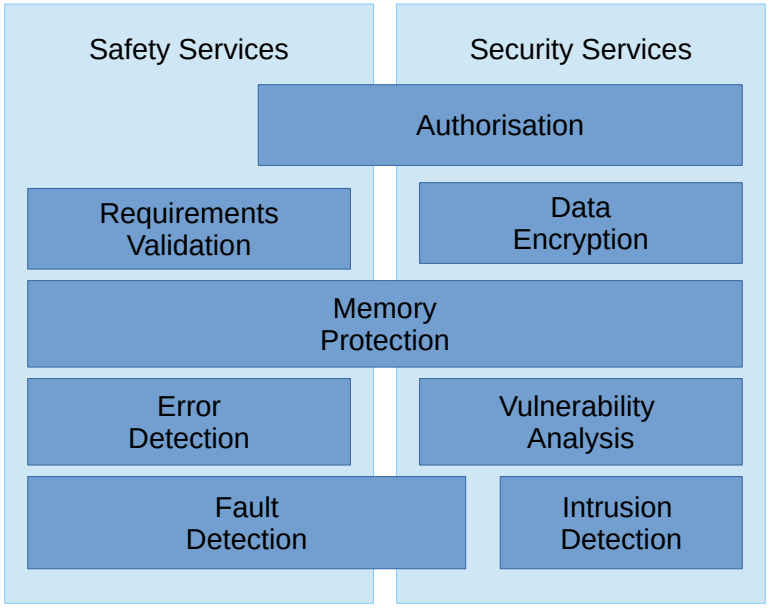

Figure 3.2: Classification of various services into safety and security services.

3.3.2 Failure Detection Service

A Fault Detection Service (FDS) is a service which is capable of detecting faults, and eventually, depending on its implementation, also *control flow errors*. Control flow errors are errors, which lead to a wrong execution sequence of the instructions of a service. Technically, the FDS can be implemented as simple timer circuit with a specified threshold time. If this limit is reached, it changes its state in order to trigger further actions, like restarting a component or activating another safety service [7]. The advantage of the FDS is the simple design, which

reduces the additional complexity of the overall system, as well as the costs. Concerning the functional principle, there exist different designs with increasing complexity, which can provide, for example, a certain time window for the response [7].

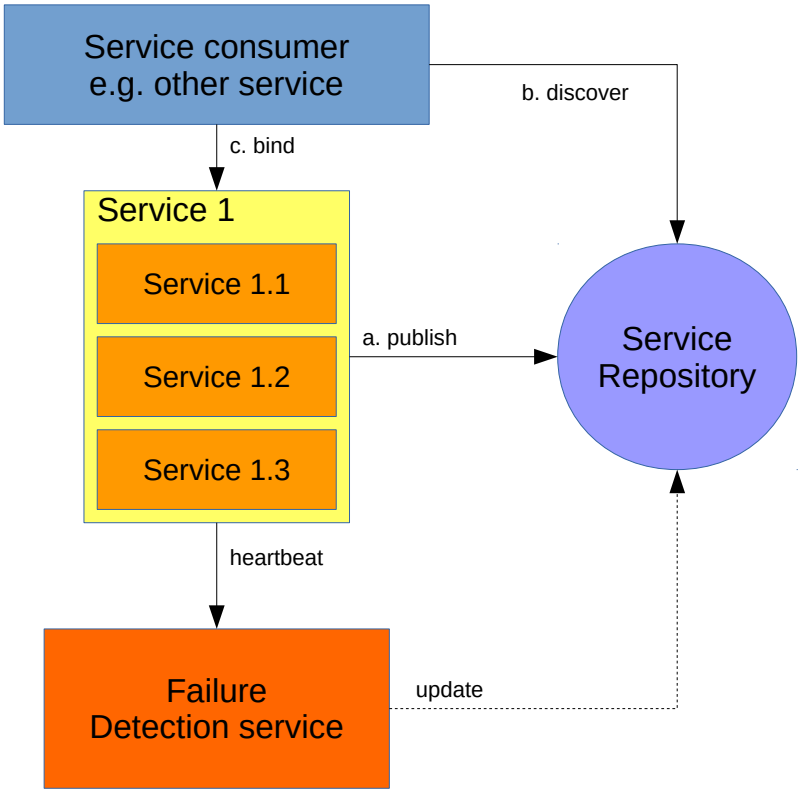

Figure 3.3: Example architecture for an *fault detection service*, like a WDT.

In the following, a fault detection service is described by means of its most prominent representative, the so called *Watchdog Timer (WDT)*.

As suggested by the name, the WDT is based on a timer, which gets reset every time a heartbeat signal from the observed service is received. There are three different basic designs: the *Standard Watchdog Timer*, the *Windowed Watchdog Timer* and the *Sequenced Watchdog Timer* [10].

Standard Watchdog Timer. With this basic setup, the service mirrored by the WDT, periodically sends a simple heartbeat signal which resets the timer and indicates that the service is alive and active. If a predefined amount of time elapsed without an incoming signal, it is assumed that a fault has occurred and the WDT changes its state [10].

In terms of *control flow errors* in a service, the heartbeat signal may, or may not, be sent too late. In the latter case, the WDT is capable of detecting the error too [10]. The probability of noticing such an error is higher the closer the threshold time is to

the time between the heartbeat signals.

Windowed Watchdog Timer. The *Windowed Watchdog Timer* is an improvement of the standard version which is capable of detecting most of the *control flow errors*. This is enabled by the application of two timers instead of one. With two timers the WDT is able to specify a time window during which the heartbeat signal from the observed service must be received. The WDT is triggered if it receives a signal outside the window, or the timer reaches its threshold [10]. This is illustrated in figure 3.4 with the $time$ on the x-axis and the Timers labeled $T1$ and $T2$. The time window for a valid reset is thereby the result of $T2 - T1$.

In case of an *control flow error* this signal is a bit ahead or past in time. The error detection coverage increases with narrowing the time window [10].

The advantage of this design is clearly that it allows the detection of more errors, but on the other hand the implementation is slightly more complex.

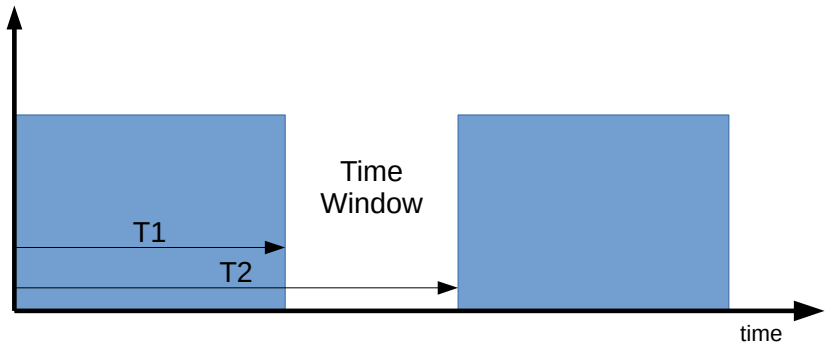

Figure 3.4: Schematic design of a windowed watchdog timer [10].

Sequenced Watchdog Timer. This design is a further improvement of the *Windowed Watchdog Timer* and bases on the same principle. In contrast to the other designs, the signal sent from the mirrored service carries a sequenced parameter. Only if the signal arrives in time and within the specified time window, this parameter is evaluated and compared to a parameter inside the WDT. If those match the sequence variable in the WDT, the variable gets incremented and the timer reseted, starting the cycle all over again [10]. The whole process is illustrated in figure 3.5.

The disadvantage of this design is the clearly higher complexity, as the *Sequenced Watchdog Timer* must be capable of holding and modifying state information as well as comparing it to received information.

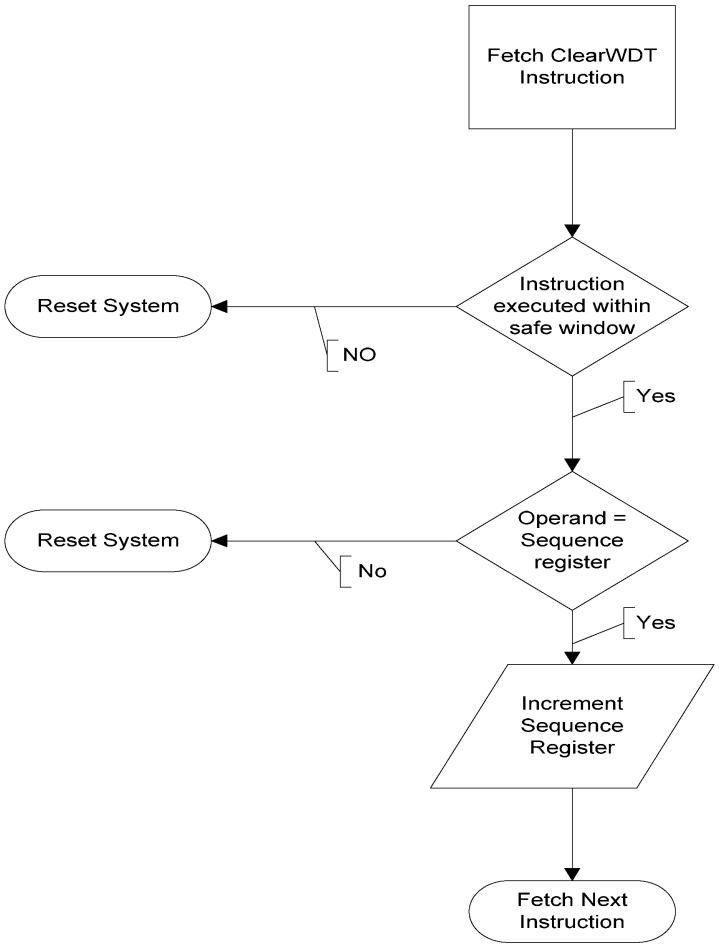

Figure 3.5: Schematic illustration of the operational principle of a *Sequenced Watchdog Timer* [10].

3.3.3 Error Detection/Masking Service

Most of the errors, especially those which do not alter the timing, remain unnoticed by the WDT. There are several approaches in the design of an error detection service, but the most simple and approved one is based on triple modular redundancy (TMR). With this approach an error detection service mirrors three individual and independent services which provide the same functionality (e.g. acceleration measurement). A comparing logic inside the error detection service compares the information received from these services and can identify an error in one of the services by means of a simple voting mechanism [46]. In event of an error, another service can be triggered for restarting the erroneous service or performing other countermeasures.

The very same implementation is also capable of performing *error masking*, because due to the redundancy and the voting system the service could also hide an error in one of the mirrored elements, without the service consumer noticing.

3.3.4 Memory Protection

Memory protection is related to safety as well as security. It is a method for preventing processes or users from accessing memory that is not allocated to them.

Former embedded systems, or such that are small in size, do not necessarily require memory protection mechanisms, because all related programs have a very specific purpose and an unintended behaviour is rather unlikely. In such cases, the overhead in runtime, when using memory protection just does no pay off [50].

Modern, large scale system, on the other hand, dispose of numerous third-party components for the interaction with the user and the environment. At the same time, the overhead in computing is no longer crucial, due to the fast increase in computing power [50]. Especially if the system is connected to a public network like the Internet, memory protection becomes also a big issue for the prevention of malicious attacks.

There are several other aspects stressing the need for memory protection in ES:

- It can serve as fault- and error detection and containment mechanism, preventing a failure of one service to propagate and infect the whole system [50].
- It protects the system from unintended behaviour of the particular services [51].
- It is an important aid for the development process and helps at debugging by identifying

"illegal" behaviour of erroneous services, resulting in a reduced development time [50] [51].

As a service, it could be implemented like the *Information Assurance* core service from the Arrowhead framework (cf. section 2.1.3), with dedicated services for authentication, granting privileges and managing authorization information.

3.3.5 Requirements Validation Service

This service should be responsible for checking the compliance of safety margins, when services are composed. For example, if a service is required to be in compliance with ASIL D, it cannot be based on another service, which can only provide ASIL B. According to its specification the requirements validation service could either prevent this orchestration, or even look for possible solutions, e.g. looking for a service with the same functionality and ASIL D, or combining two of the ASIL B services.

A service like this is, surprisingly, mentioned nowhere throughout literature, but according to various findings this is a crucial mechanism in order to do not violate functional safety requirements when composing services.

3.4 Service Development Process

In order to be in compliance with given design rules and standards, the development of services has to follow strict protocols.

The development stages considered in this section are an adoption of the development stages, provided by Erl et al. in [30, p.116]. In detail, the first four stages are the object of investigation. The stages are renamed to fit for the development of a single service instead of an overall SoA and are denominated:

- *Service investigation/planning*,
- *Service inventory analysis*,
- *Service oriented analysis* and
- *Service oriented design* [30, p.116].

3.4.1 Service Investigation/Planning

This phase is concerned with the initial layout of the service. It is the phase where necessary requirements are listed and explored. There are several questions which need to be answered during this stage:

- What is the scope of the service?
- What are required capabilities?
- Which capabilities are not required?
- What are the safety requirements concerning this service?
- Should this functionality be implemented as service at all?

3.4.2 Service Inventory Analysis

During the service inventory analysis the service inventory (cf. section 2.5.2) is searched for services which are required in order to build up the desired service. This simplifies the development because much of the required functionality is already provided by other services and at the same time this step is responsible for preventing redundancies.

The outcome of the service inventory analysis phase is a so called *service candidate*. This denotes a conceptual service model before it is implemented by means of a specific language. According to [30, p.42], the concept of a language independent service candidate is applied, because the service undergoes a lot of changes in these early stages of development. Nevertheless, this may not be practicable in reality and it is not unlikely that the templates for the service contract are used and extended from the very beginning of the development process.

3.4.3 Service Oriented Analysis

During the service oriented analysis phase the service candidate is reviewed and checked in terms of *naming* and *normalisation*.

Service naming. The naming of the service candidate must be in accordance with other, existing, services [30, p.206].

In terms of automotive, the naming is governed by certain standards, like AUTOSAR, which proposes naming conventions in their **SW-C and System Modelling Guide** [52].

A unified naming convention is quite helpful when dealing with standardised interfaces and provides a possibility to include relevant meta data, like the related system or intended functionality, into the name [53].

Service normalisation. Services within the same service inventory shall not have overlapping boundaries. In other words, redundant logic should generally be avoided, as it would violate the concept of a SoA. Accordingly, the services are forced to use existing services if those offer the required functionality [30, p.207].

Service Candidate Review. The final phase of this stage is a review by the related developers. A possible outcome of this review is the approval of changes or extensions to the service candidate [30, p.210].

In order to ensure an unbiased outcome, this review could be conducted by "external" people, which have not been included into the development process up to this step, but still have a thorough knowledge of the SoA principles. Those people might think of a quite different approach for the very same problem and could raise new questions concerning the proposed design and composition.

A review can also take place if an existing and already implemented service is extended by one or more new capabilities [30, p.210].

3.4.4 Service Oriented Design

Erl et al. [30, p.86] describe this phase as:

> "Service-Oriented Design subjects this service candidate to additional considerations that shape it into a technical service contract in alignment with other service contracts being produced for the same service inventory."

The aim of the service oriented design phase is to physically establish the service contract by filling out the corresponding templates. It is initiated when sufficient analysis has been conducted and ends with a finished service contract as output.

3.5 Use Case Scenario

As final part of this investigation, a short use case scenario was conducted. In detail, the development process of an *error detection service* was investigated by means of the development phases featured in section 3.4. Due to the scarce reference material related to this topic, the use case scenario is rather short and quite theoretical. However, it provides a good example on what the development process of a service may look like.

3.5.1 Service Investigation/Planning

Scope of the service. The service should be capable of detecting an error within a given ECR and act accordingly. Therefore it needs the signal of all the sensors it should mirror, as well as clock signal for creating sampling times.

Required capabilities.
- Detection of an error in one of the sensors.
- Restart of an erroneous sensor.
- Purging the service from the service repository if more than two sensors fail and errors can no longer be detected.

Non-required capabilities.
- Detection of a fault.
- Detection of a failure.

3.5.2 Service Inventory Analysis

The error detection service will require:

- A *clock service* for creating sampling times,
- A *fault detection service* for detecting a fault in one of the mirrored services,
- A *management service for the service repository* to update the repository in case of an erroneous service, and additionally perhaps
- A *service for restarting another service* which is erroneous.

During operation it will also need the redundant service inside the ECR, whose functionality shall be checked for errors. Of course, they should feature different implementations on independent hardware components, so that an error could not emerge in multiple services at the same time.

3.5.3 Service Oriented Analysis

Concerning the naming, the example service should be in accordance with the AUTOSAR naming conventions [52]. Hence, a suitable candidate would be **error_detection**.

The *service normalisation* and *service candidate review* are not really doable, just theoretically. Therefore, it shall be assumed that the example service has no overlapping functionality and has passed the review.

3.5.4 Service Oriented Design

Unfortunately, the service contract templates, which are designed by Arrowhead, were not yet available at the time this thesis was written. Accordingly, there could be no example contract be established.

3.5.5 Possible Implementation

At the end of the first four phases, which are concerned with the conceptual development, the service contract is issued. Subsequently the actual implementation of the service is conducted by a developer, who was (most likely) not included in the preceding design phases. Therefore the contract must provide all the necessary information for the implementation process, leaving no ambiguities or open questions.

It is then up to the developer to decide how the service will be implemented, e.g. which programming language or approach to use. The outcome is a certain architecture, which can be based on any arbitrary technology.

A possible architecture resulting from the service of this use case is a triple modular redundancy approach (cf. section 3.3.3), as depicted in figure 3.6.

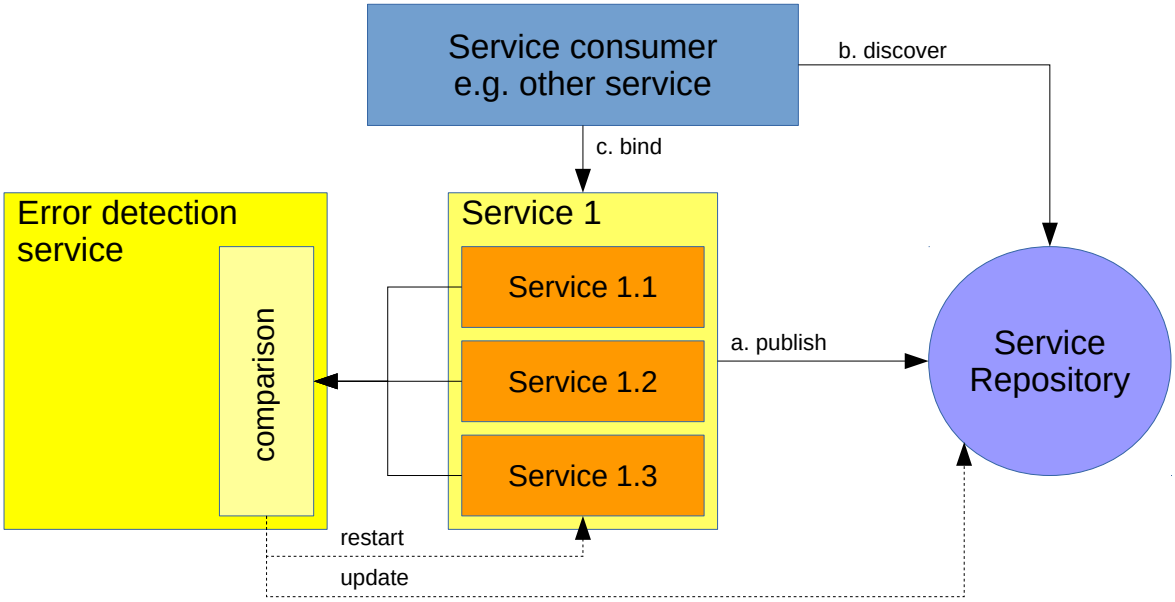

Figure 3.6: Possible architectural implementation of the example service.

Chapter 4

Discussion

Most of the concepts and principles featured in chapter 3 are quite theoretical and based on perceptions which have derived from meetings and discussions with experts from this area. Nevertheless, the plausibility and validity cannot be guaranteed. On the one hand this is due to the state of the art of this research area, with few meaningful publications available. On the other hand, it is due to the non-disclosure regulations of companies which operate in the functional safety and security area.

However, the document from which most of these concepts originate, has been created with the aim to demonstrate possible implementations or concepts to the EMC2 project group, since the SoA concept is quite new and unfamiliar to most of the project members. Accordingly, the here presented information states the company's way of looking at things with no claim to correctness or completeness. The SoA paradigm for ES like vehicles or aircraft is still quite at the beginning of its development, which is the reason why it is impossible to make any accurate predictions. To sum up, the actual purpose for which the use case and other concepts from chapter 3 were developed, namely the creation of a uniform knowledge base, are fulfilled.

Chapter 5

Conclusion

In order to optimise the amount and maintainability of code, the concept of software reuse has been present since the very early days of software development itself. The SoA approach, which is treated within this thesis, is the state of the art concept in terms of software reuse. The underlying idea with this principle is that functionalities are implemented by means of so called services, which hide their internal logic and allow connections only through well-defined interfaces.

Although already widely applied in other domains, the SoA concept has not yet been applied for ESs like vehicles or aircraft. On the one hand, because of pure technical constraints due to the implemented hardware which is not optimised for the application of the SoA design paradigm. On the other hand, this is due to the safety-critical aspect of such systems and the ISO 26262 functional safety standard which does not issue any requirements concerning services or the like. Generally, functional safety in **safety-critical embedded systems** was an area with various unsolved questions and issues at the time this thesis was written. A third drawback, which has not been mentioned so far, is the economic factor. The SoA for automotive requires dedicated hardware which needs to be developed and adopted accordingly. In turn, this leads to high development and testing costs, before there is any benefit observable. At the same time it is hard to communicate the advantages of a vehicle with a SoA inside to the end user. The benefits become only obvious when there is a lot of environment and other vehicles which allow connection and communication with. In other words, all these concepts and ideas need a huge amount of resources and promotion to get them started in a reasonable manner.

Nevertheless, the SoA paradigm offers a wide range of advantages and benefits and is perhaps a necessary prerequisite for next generation's vehicles and aircraft. Hence it is no surprise

that a lot of research has been conducted recently with this respect. The Work Package 1 (**Embedded Systems Architectures**) of the EMC2 project is currently in the first year of a total of three. This indicates that an actual implementation of a SoA in a mass produced transportation system may still lie quite some time ahead; but the eventual emerging of this kind of technology seems just a matter of time.

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