School of Engineering & Design – Electronic & Computer Engineering

MSc Distributed Computing Systems Engineering

Brunel University West London

Simulation and Performance Analysis of a Distributed Position Correction Scheme for Unmanned Aerial Vehicles

Interim Report

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List of Abbreviations

API	Application Programming Interface(s)
CCU	Central Control Unit
DOF	Degrees of Freedom
FPGA	Field-Programmable Gate Array
GUAV	Gliding Unmanned Aerial Vehicle(s)
HIL	Hardware In the Loop
HSE	University of Applied Sciences Essslingen
HUAV	Hovering Unmanned Aerial Vehicle(s)
IMU	Inertial Measurement Unit
MAV	Micro Aerial Vehicle(s)
MBD	Model Based Design
MEMS	Micro-Electro-Mechanical System
MIMO	Multiple-Input and Multiple-Output
PID	Proportional-Integral-Derivative
RF	Radio Frequency
SBC	Single Board Computer(s)
SLAM	Simultaneous Localization And Mapping
UAV	Unmanned Aerial Vehicle(s)

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1 Introduction

During the last years the interest of robotic science and the development of robots increase enormous. Reasons for that are, the unstoppable technological progress of hard and software techniques, but also the necessity to replace humans with machines in dangerous, monotonous or unreachable industrial environments (medical, space, aviation and so far). One area of these interests is the aerial platform and the realization of Unmanned Aerial Vehicle(s) (UAV), which are mostly controlled via remote control or fly autonomous. These aircraft vehicles have several capabilities like in military or rescue operations with special environments like a burning house. For such indoor operation it is important to focus, that some kind of feedback sensors like GPS-sensors could not work satisfactory. In such cases UAVs faces problems with the self stabilization, because their physical behaviour is in generally unstable [Mic10, p.1 Introduction]. Most of the approaches to stabilize UAVwork with a clever combination of sensor equipment and control algorithms. Mostly this controller uses a Inertial Measurement Unit (IMU)which is mounted on board and includes accelerations sensors to detect movements in the given Degrees of Freedom (DOF). Actual acceleration sensors, which are used for this purpose, are Micro-Electro-Mechanical System (MEMS)or fiberoptic sensors which have a finite precision and unacceptable error propagation in case of integration for velocity or position detection [Mar08, p.p.11-13 Function Principles of MEMS, Sources of Error].

This problem also is a field of research at the Quadrocopter project of the University of Applied Sciences Essslingen (HSE)[HSE10, Website].

Figure 1.1: HSE Quadrocopter

1.1 Project State

The quadrocopter project of the HSEwas launched with the goal to build a system from the scratch, which is developed by students, scientific workers and Professors. In a first project the Printed Circuit Board which hosts the parts necessary to control the quadrocopter was designed by students at the faculty of Mechatronics and Electrical Engineering in Goeppingen. This project groups' focus was then on the simulation, implementation of the basic functions and visualization of the actual condition of the aircraft. The first two project groups already show the benefit of this project, a multidisciplinary development including hardware design, application development, embedded programming, simulation and the interfaces between these special fields. In the year 2009, the Faculty of Information technology adopted the development of the project with the aim to solve problems which came up in the previous development and to redesign the soft- and hardware architecture.

So a new hardware design was developed in a corporation between the two faculties with the outcome of a Central Control Unit (CCU)which can detect inertial movements in six DOFand can control the four actuators of the quadrocopter via so called brushless controllers. One of the biggest unresolved problems since yet is the development of a robust controller and the elimination of drifts which especially come up at the hovering state. The practice and the experience of previous developments show, that it is indispensable to proof new developments with a simulation before they will be realized at the real UAV. So the main topic and the focus of this Master´s Thesis will be on the development of a simulation which shows potential solutions of the mentioned problems and the research and evaluation of the outcome results.

2 Background to the project

2.1 Problem Description

Improvements of high density power storage, integrated miniature actuators and sensors, facilitate the development of Micro Aerial Vehicle(s) (MAV)and new areas of research for unmanned and autonomous flying systems [Sam04, p.1 Introduction]. This new area of interest brought also a new area of problems. One of these is the fact that the pilot of the aerial vehicle does not exist, because the UAVflights autonomous or the pilot observes and controls the UAVvia remote control. In both cases it is necessary that the UAVsystem can detect its absolute position, to provide the pilot a better quality of control or furthermore to manoeuvre autonomous. The following articles also describe this problem with different views and approaches [Sla09, p.2 Localization and path planning] [Kar10, p.1 High precision aircraft positioning] [Seb08, p.2 Teleoperated Robot Control].

This necessity of location determination requires measurement unit, which provides the detection of the movements in the given DOF. Because of low-cost and low-complexity reasons, the most popular components which are used to reach a nearly satisfactorily level of flight stabilization are inertial sensors. These sensors combined together called IMUand have the ability to detect the acceleration of translational or rotational movements.

Furthermore a control system can be used in a closed loop together with the IMUand can correct theoretically nearly every disturbance in a continual system [Sam07, p.p.45-64 System Control] [Ped05, p.p.49-51 Control Strategy]. The limitation of resolution of the sensors and the necessity of integrating the acceleration values for position and velocity determination, have in real systems a big impact in aspects of error propagation and detection of smoothly movements [Bea08, p.5 Low-acceleration Drift]. For a better appreciation of the movements, the following figure visualizes the influence of the thrust in relation to the movements in the DOFs. Thereby the values of ω [rad/sec]represents the least needed speed of rotation, for creating the required thrust for the hovering state. This state can be described as a state, in which forces in the x- and y-axis equals zero and the uplift force in direction of the z-axis has the same absolute value as the gravitational force. The value of $\Delta\omega$ characterizes the purposed deviation of the required force in hovering state and is used for navigation of the quadrocopter.

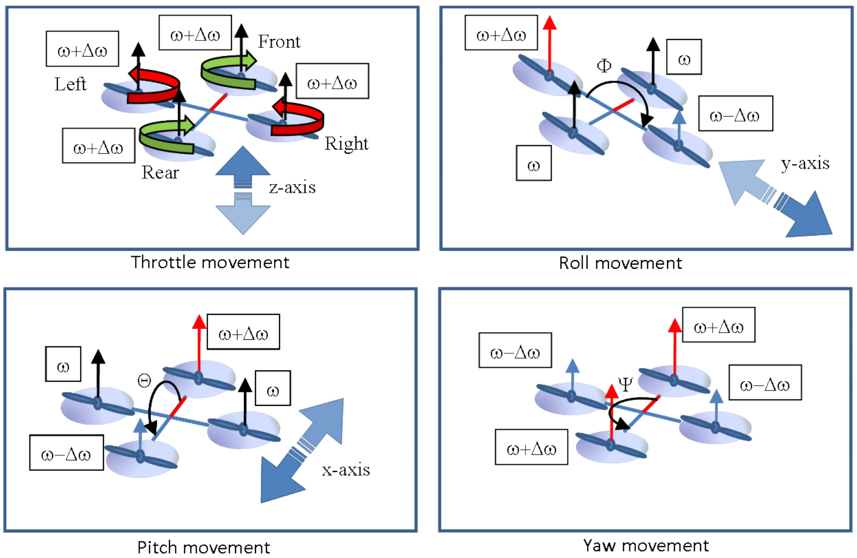

Figure 2.1: Degrees of Freedom of a quadrocopter

To keep the equilibrium of rotational kinematics and to prevent self-rotation, the motor direction of rotation equals crosswise. The quadrocopter has six DOFwhich can be distinguished as angular and translational movements. Translational movements can be executed in x-, y- and z- axis. Accelerating all rotors with the same thrust ω to the value of $\Delta\omega$ will affect a movement in z-direction. Movements to the negative direction of the z-axis are possible, if the thrust of the four rotors is smaller as the gravitational force of the aerial vehicle.

The roll movements can be described as a change of the angle around the x-axis. Thereby the left and right rotors execute a force difference by slowing down the one and simultaneous increasing the other thrust with $\Delta\omega$. Related to the thrust difference and angular movement, the aerial vehicle creates a force to the y-axis. Equivalent to roll, the pitch movement is executed with a change of the angle around the y-axis. Also the pitch movement creates a translational movement across the x-axis. Pitch and roll can only reach a stable angular state and accelerate to the x- or y-axis, if the value of $\Delta\omega$ is the same at the diagonal rotors. Otherwise, the quadrocopter would pure rotate across the corresponding axis.

The yaw movement is a rotation around the z-axis. This angular movement results in combination of pairwise different thrusts and takes as long as the thrusts are different [Ped05, p.p.8-11 Quadrotor model and system].
Synthesizing the weaknesses of MEMSlike noise or the limited resolution, together with the characteristics of the kinematics of the quadrocopter shows the problems which come up in case of MAVcontrol with a IMUwith MEMS. As mentioned smoothly accelerations could be a drawback for the control system, because this kind of accelerations gets lost in the sensor noise.

Regarding the kinematics of the quadrocopter, we have seen that translational movements can only be reached with angular movements across the x- and y-axis of with increasing or decreasing the thrust on every rotor in the z-axis. Imprecise noisy sensors would affect a wrong thrust regulation at the actuators. Thereby it is highly improbable, that all four rotors affected by the noise equal and accelerate in the z-axis. More probable as a uncontrollable acceleration in the direction of the z-axis, is that pairwise two rotors have the some drift and create so an unexpected yaw rotation. Finally the most probable will be a wrong thrust regulation at one rotor, but for a short time interval. So the most likely error drifts will exist at the x- and y-axis. So the hovering state will be nearly impossible to reach just with MEMSacceleration sensors, because the x- and y- movements have to be zero.

The following figure 2.2 shows the described problem area of MEMSsensors in the concrete case of the sensors which are mounted at the quadrocopter CCUof the HSE. The mechanical characteristics of the translational acceleration sensor [ST 05, pp.37-39 Typical performance characteristics] were simulated under consideration of the change of the position of the quadrocopter and the applied acceleration.

We can see, that accelerations which are small enough, get lost in the sensor noise and are invisible for the quadrocopter. Furthermore the quadrocopter reacts in t=12 if the acceleration transcends the threshold value of the sensor noise.

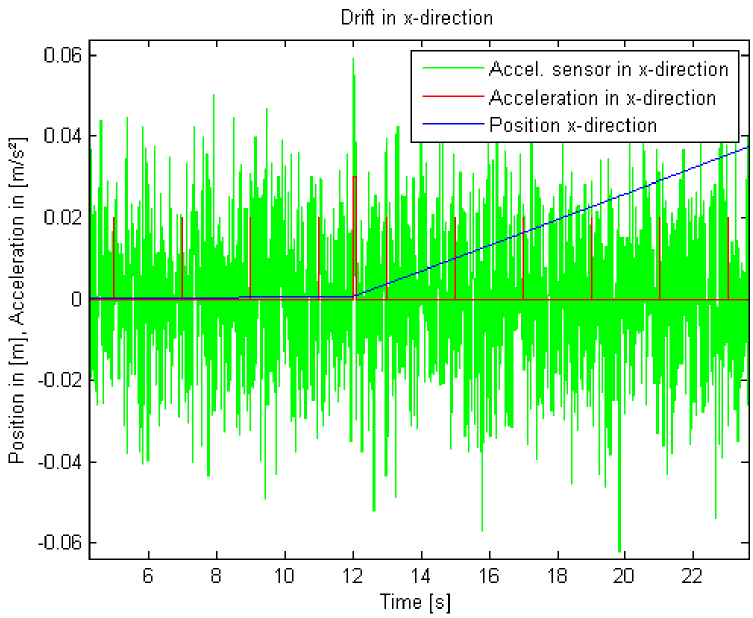

Figure 2.2: The impact of sensor noise

3 Initial Survey

An enormous quantity of researches, which is sponsored by industry companies or universities, was executed to find a better approach to stabilize UAVby using different sensors. Movement detection approaches, which are ultrasonic, sonar or Radio Frequency (RF)based, show that it is necessary to have known reference points to get a reliable result [Jue09, p.2 Ultrasound indoor localization with reference points][Nir02, pp.4-5 Radio Model Localization]. The problem of this approach is that the environment has to be prepared before the UAV flight. This preparation is a drawback in point of flexibility in different operation places. Anyway, approaches with ultrasonic, RFor sonar sensors show that the localization of UAVneeds a kind of global feedback to correct the UAVabsolute position. One of the first motivations for a vision based sensor was presented by Ettlinger et al. [Sco04, pp.1-2 Visual-Based Localization and Control]. In this paper, the authors suggest, that vision is the only practical solution for obstacles of flight stability and showed an On-board approach for a Gliding Unmanned Aerial Vehicle(s) (GUAV)by detecting the horizon with a forward looking camera and estimating and control the flight attitude. Further vision based attitude control approaches also were used for Hovering Unmanned Aerial Vehicle(s) (HUAV)with the difference of a down looking camera for reference point free movement detection or an Off-Board camera which tracks the global position of the UAV.

3.1 On- vs. Off-Board Camera and Image Processing

The Off-Board camera approach was researched by Altug et al. [Erd02, p.76 Localization and Control with an Off-Board camera], with the result of a less sensitive feature detection and position localization as the On-Board camera approach. Off-Board camera tracking is also shown in the developments of extremely reliable and precise localization of a UAVand it is actually used in the development of aggressive autonomous flights of multiple MAVin the experiments of Mellinger et al. [Dan10, Trajectory Generation and Control with Off-Board cameras] [Dan07, pp.363-364]. The advantage of the Off-Board camera tracking system is that the image capturing and position tracking is executed outside the UAVand prevents complex On-Board calculations for movement and position estimation. The drawbacks of this Off-Board Tracking methods are that they need a previous prepared testbed for the flying environment, which is build up with a motion tracking system [Nat10, pp.1-2 The GRASP Testbed].

Problems, such as a limited power resource, a poor level of algorithm complexity for image processing resulting from the limited calculating On-Board performance and the endeavour to economise weight, lead to outsourcing the image processing to a remote system which is not concerned to the On-Board problems. Langer et al. [Sve08, pp.5-7 Off-Board Image Processing] uses an Off-Board image processing to track a landing pad for autonomous landing. Thereby the images are transmitted in this approach over Wifi communication to a base station, which tracks the landing pad and sends back information of position control. Thereby it was shown that the landing algorithm has to run at maximal 100Hz to work with the transmitting delays of the images.

This landing algorithm shows that it is possible to outsource successfully the image processing in consideration of the sample rate which the algorithm needs. By regarding the drawback of the image transmission delay of the Off-Board image processing, On-Board approaches were developed with the focus to the Real-Time behaviour. Tippetts [Bea08, pp.21-22 On-Board image processing with an FPGA] realized an On-Board approach with a Field-Programmable Gate Array (FPGA)which uses a complex feature tracking algorithm but runs with 100MHz sampling rate. The characteristics of the feature tracking with a FPGAcan result a fast movement tracking method, but it is not an efficient method in the behaviour of power consumption because the hardware is not optimized for the image processing tasks.

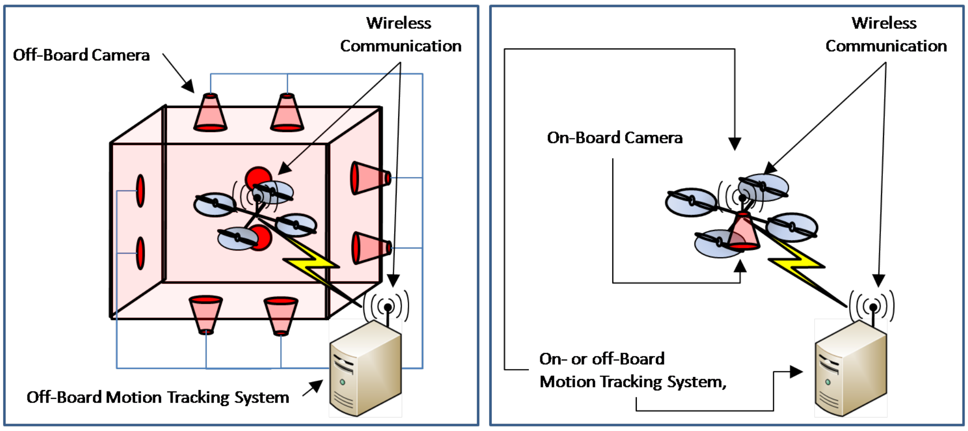

Figure 3.1: On- and Off-Board camera and motion tracking system approach

3.2 Hardware vs. Software-based image processing

In contrast to the drawbacks of FPGAs, Langer et al. [Sve09, On-Board image processing with mice sensors] and Beyeler et al. [Ant09, pp.4-5] showed an approach for detecting the spatial movement of a UAVwith optical mice sensors which have an optimized hardware for image processing and are lightweight.

These sensors calculate the optical flow of the captured images and estimates the movement direction of the UAVin hardware and can provide a high sample rate. In contrast to the fast movement detection, a disadvantage, is that these sensors have limitations related to the operating environments. These limitations are the concrete light and distance range which is required from the manufacturer [ST 05, pp.7-15 Limitations of the operating environment]. The most of the experiments with a stabilisation approach with mice sensors uses optical lens to reach a higher degree of operating distance, but the effort in most of the cases is not satisfactorily to the results as Langer et. al have shown [Sve09, p.6 Performance of the optical flow based position controller]. Software based image processing approaches have a more flexible extension and change behaviour, but they work not as fast as hardware based approaches. Further advantages of software based image processing are, that the most of the commercial and open source computer vision Application Programming Interface(s) (API)also provide implemented estimators and filters to correct the captured input and to decrease noise of the images. Stowers et al. realized a heading estimation for a quadrocopter with an onboard Single Board Computer(s) (SBC)which runs the open source computer vision toolkit OpenCV[Ope10, The OpenCV Reference]. This software based image processing approach shows strengths in the modularity of the image processing architecture and in the interchangeability of the vision system [Joh09, pp.1-6 Software Based Vision Processing][Gar08, Software Structure and Porability].

3.3 Vision based movement detection approaches

Sequential captured images contain a huge amount of information about the absolute and relative movement of objects in every direction. So several vision based movement detection approaches were researched in the topic of UAVstabilisation with different requirements to the information which extracted from the vision process. A simple approach for a relative vision based control of a UAVwas implemented by Boabdallah [Sam07, pp.110-114 Position Sensor] by using a down looking camera and the Canny edge detector [Joh86] and the Douglas Peuker Algorithm for curve equalisation [DP73]. The drawback of this approach is that the field of vision must contain forms with edges which mean that the approach cannot result a satisfactory result if no edges are detected. A further approach for detecting relative movements and to build up a map for autonomous navigation, is visual Simultaneous Localization And Mapping (SLAM). This approach tracks features in the field of vision and reconstructs a relation to tracked features of previous images. The realization of SLAM[Bri07] in a UAVwas executed in the work of Bloesch et al. [Mic10] under consideration of real-time characteristics. The behaviour of the algorithm shows that the localization of the tracked features and the simultaneous mapping has a big impact at the time delay of the calculation. So the experiments and the control algorithms were researched and designed for 7.5Hz sample rate. Another popular tracking method for movement detection is given with the Optical Flow, which can be described as movement observation of tracked objects or pixels in a sequence of images. Algorithms to calculate the Optical Flow were introduced by Horn and Schunk [Ber80], Lukas and Kanade [Bru81].

A few years after introducing the Lucas-Kanade-Algorithm, Lucas described the theoretical approach of visual navigation by using the Optical Flow. Thereby he described the possibility to detect movements and to calculate correspondence velocities. These velocities can be combined to a vector field which can describe movements in every direction [Bru84, pp.40-45 Optical Navigation Theory].

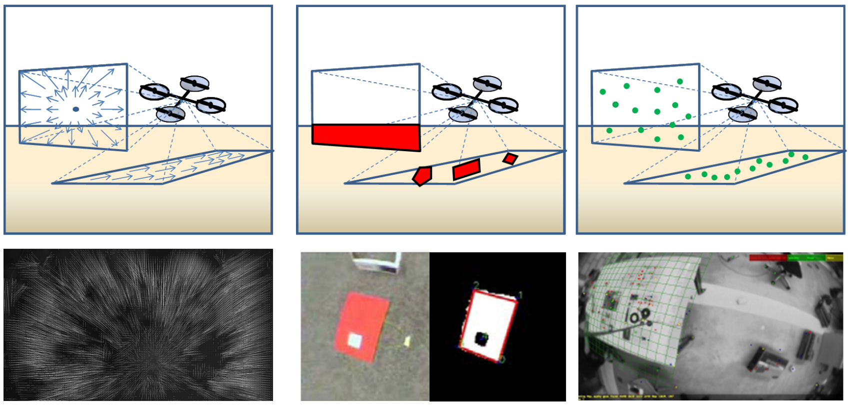

Figure 3.2: Samples for UAV stabilisation with Optical Flow, Edge detection and SLAM

3.4 Control Approaches

The closed loop feedback architecture is an approved method for controlling systems and nearly used in the most of the systems controls in industry and society. So the most of the researches in the UAVstabilisation topic were and still are executed with closed loop control architectures which are built up as Multiple-Input and Multiple-Output (MIMO)systems. The differences between the researched approaches are the amount of the inputs and outputs of the physical process, the type of controller, the used measurements and the sampling rate. Thereby the type and behaviour of the controller is close related to the measurements and the physical process [Ric01, p.3]. The classical control approach using Proportional-Integral-Derivative (PID)controler was researched in several HUAVprojects [Ved08, pp.24-31] [Sam07, pp.43-68]. These researches show that the PIDcontrol is not robust enough to handle with measurement errors and to control multiple DOFs. So the most of the released control approaches with PIDtechnique extends the control architecture with estimators and filters to get more precise measurements. Another approach for control improvement was introduced by Luenberger [Dav71] and describes a closed loop control approach, called state-observer, which simulates the process in real time parallel to the true process by using the input and output vector of the closed loop system and corrects the control strategy. Bloesch et al. [Mic10, p.5] have shown in their research, that the problematic of sensors with non-negligible time delay can be solved to an adequate result by using a state-observer.

The reason for that is that the state-observer allows configurate and to control the stability behaviour of the closed loop feedback architecture. If a process can be observed or furthermore controlled, is related to the states in which it can be and furthermore to the measurements of the DOF[Ric01, pp.632-636 Controllability and Observability]. In this project it has to be determined how correction values which are provided from the optical sensor with a slower sampling rate, can include into the control algorithm of the aircraft.

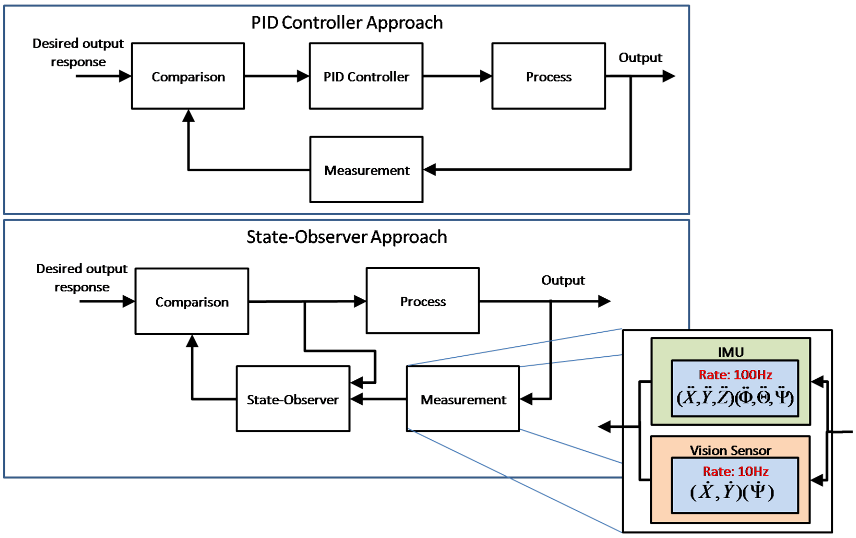

Figure 3.3: PID-Controler and State-Observer in closed loop System with variable sample sensor rates

3.5 Proposed Approach

This chapter shows several approaches for movement detection and stabilisation of UAV. The found methods were critically analyzed and assessed with the result to investigate the following techniques which are shown in figure 3.4. The proposed solution to eliminate the stabilisation problems of the quarocopter has to be vision-based for achieving the goal of flexibility and independence of operational environment. Related to the off-board image processing, the problem of the processing delay, could be solved with a state-observer. Furthermore the optical movement detection should work without reference points. So the optical flow method has to be researched by using a software-based detection approach for more flexibility and replaceability. Because the approach of the flight control is teleoperated and the flight stabilisation does not have to provide aggressive flight maneuvers, it is simpler to realize the camera view on-board. This proposed solution has to be simulated to check the feasibility and to determine the limitations.

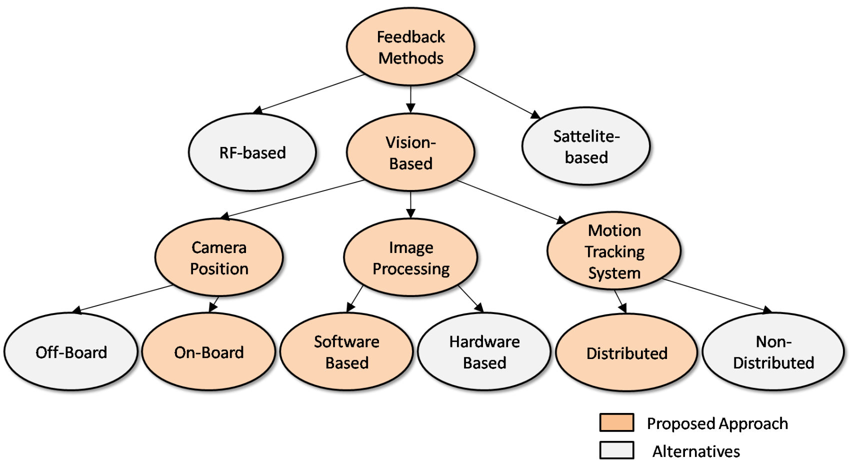

Figure 3.4: Proposed Approach

4 Aims and Objectives

The aim of this dissertation is to provide a simulation architecture that can be used as prototype development platform for a distributed visual movement detection and control of a quadrocopter. Furthermore the characteristics of the distributed image processing and movement detection have to be analyzed in relation to the variation of configurations and critically assessed.

One essential objective is that the configuration of the simulating components provides the option to simulate a range of hardware components which are not purchased until now. By way of example the simulation of the on-Board camera has to provide options of configuration for the resolution, color intensity, blur and so far. The simulation of the communication between UAVand host also has to provide a variation of transmission rate and further behaviour which could affect the visual movement detection at the base station. The efficiency in relation with the quality of function is an important indicator for the success and acceptance of the distributed movement detection approach. So it is important to get an insight to the possible characteristics of the simulated components with the result to find a way which satisfies the efficiency and quality aspects.

Another important objective is that the interfaces between the simulating components are clearly specified and allow a way of modular exchangeability of simulation components with the real objects.

This purpose has to allow a more precise investigation of the behaviour of the real hardware related components and the option to test software for the UAVtarget, like the On-Board control algorithm, at the base station.

The realization of the simulation therefore has to provide an encapsulated and flexible architecture and has to simulate behaviour like delays and jitters for simulated components. Thereby the simulation has to adjust a real-time-behaviour in the complete simulated environment and to allow so measurements and prediction of feasibilities with the simulated configuration.

5 Experimental and Investigative Methods

5.1 Development Process

During the initial survey we have seen many approaches for aircraft stability and movement detection of UAV. The most of these approaches were developed iterative under consideration of the upcoming problems and obstacles [Erd02, Erd03, Iterative Development, Single and Dual Camera Feedback] [Sve08, Sve09, Iterative Development, Landing and Position Control Development]. This procedure model also will be appropriate to this project, because the potential risks are difficult to identify. So the outcome of the development process have to be a prototype which can be evaluated, tested and extended. A process model, which provides an appropriate structure to face the iterative prototyping strategy under the consideration of the risk aspects, is given with the spiral model. The classical spiral model has typically four phases in which the product is developed in an incremental evolutionary process. Derivates of this classical model which focus the customer evaluation for quality improvements may three, five or six phases. In the context of this project, the classical four phases spiral model is used for scientific and feasibility study and does not have to provide further customer communication phases [Rog01, pp.36-38 The Spiral Model].

A typical cycle of the four phases spiral model (5.1) begins with the identification of the objectives which have to be elaborated like performance, functionality, flexibility and so far. The next step is to evaluate the alternatives relative to the objectives and constraints and to determine significant sources of risks. After that, the next level iteration of the product is planned. In the special case of this project it is comfortable to use Model Based Design (MBD)in this phase by using the results of the previous phase as input. This input can be a planed prototype or requirements which describe the changes to execute. The output of the MBDphase can be used again in the planning phase for the next iteration [Bar88, pp.64-69 Spiral Model of the Software Process].

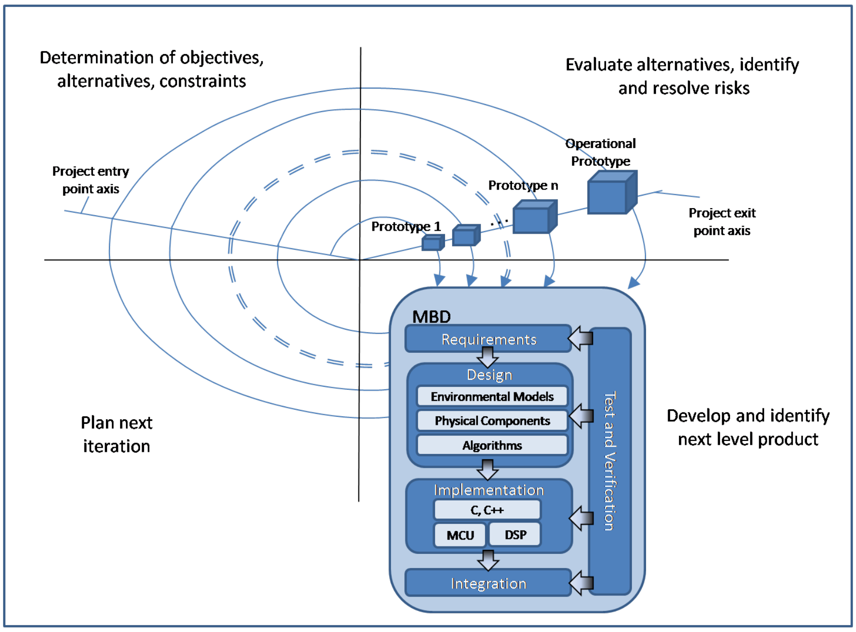

Figure 5.1: The Spiral Model in combination with Model Based Design

5.2 Model Based Design

MBDis a popular method to encounter problems which come up in the development of mechatronic products. These systems almost involve mechanical, electrical, control and embedded components which are developed in different teams of engineers with a specialized focus on the part of the complete project. Some of these components are related on the results of other components before they can be developed. This problem can be solved with Model Based Design and the advantage to develop modules of the complete project by simulating their environment. So the development can run highly parallel with the benefit that the modules can be continuous tested in each phase of the project [Dou09, pp.1-2 Challenges of mechatronic product development].

The development section in figure 5.1 includes the phases and the corresponding key capabilities of MBD. The first phase of MBDis the realization of the researched and required components into a simulation environment. Thereby physical components, environmental model and algorithms are abstracted to systems by using domain-specific modeling tools with a well defined edges and intercommunication. The developed systems in the design phase can be tested simultaneously to analyze the system performance and correctness. Other key capabilities of MBDare given in the implementation phase. The MBDtool Matlab allows to generate embedded code from the designed systems or to combine handwritten code with the build simulation of the design phase. So the implemented modules can be similarly tested in the adopted simulation environment. Finally components which have passed the tests at the implementation phase can be integrated together.

Ultimately the final product can also be tested with the MBDtool by simulating the environment of the product e.g. in a Hardware In the Loop (HIL)test bench. [Mat10, Model Based Design, MathWorks]

5.3 Overall Design Model

The overall design model gives an overview of the components of the simulation which has to be realized in the context of this project and the corresponding applied techniques. As visualised in figure 5.2, the left side of the simulation abstracts the embedded system of the quadrocopter. Inside these components the plant or physical model has to simulate the movement behaviour in the DOFof the quadrocopter. Furthermore the controller has to correct the position of the UAVand to compensate outside disturbances with information of the IMUand the distributed correction value of the base station. The environment simulation which has to include the underground and disturbances simulation will be triggered to start just as the rest of the simulation with a task which describes the ideal flight manoeuvre. The transmissions of the camera IMUand correction data have to be delayed in relation to a configurable transmission rate. The image processing has to be executed with an application, realized in OpenCV [Ope10, OpenCV Project] and invoked by Matlab [Rac10, OpenCV and MEX-Functions in Matlab]. The calculated drift from image processing finally has to be compared with the received values of the IMUto determine the position correction value. This correction has to be transmitted to the embedded system and included in the correction of the controller.

The novel aspect of the project here is reflected in the approach to simulate the complete embedded system, the transmission process, the base station and to realize the image processing in an application. The strength of this approach is that the simulation gives better results and a deep insight to the concurrent processes and helps to understand the challenges and limitations of the investigated scheme.

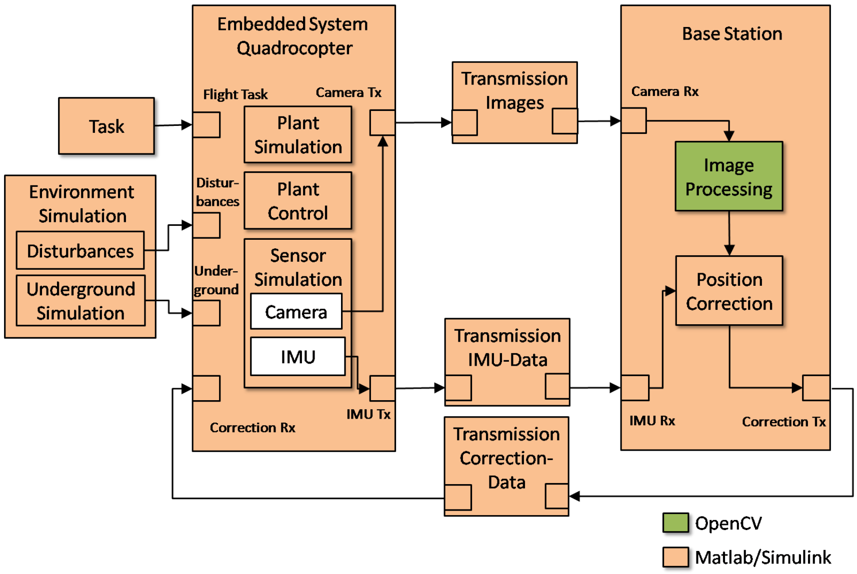

Figure 5.2: The Overall Design Model of the Simulation

6 Project Plan

The Project Plan of this Master's Dissertation is visualized in figure 6.1. The critical, red path is the result of the parallelization of some work packages. These packages mostly are independent and include idle time delays, so that it is more efficient to parallelise them. For example we can regard the simulation and research together with the Master's Thesis documentation. These work packages can be parallelized, because the simulations which have to be executed are time intensive and not a basic part of the complete documentation. Furthermore we can see that one cycle of the spiral model will be executed in the context of this Master's Thesis including an iteration of the MBDprocess.

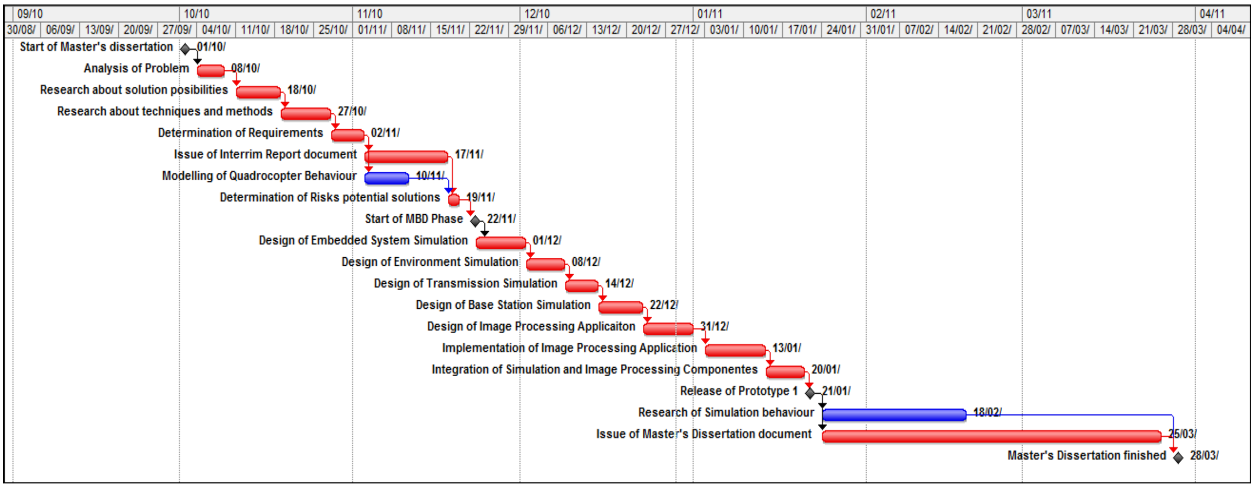

Figure 6.1: The Project Plan

7 Deliverables and Outcomes

The expected outcome of the Master's Thesis is the research and feasibility study of the distributed position correction scheme which has to reflect the improvements of drift eliminations. This has to be realized with a simulation prototype which reflects behaviour of the real components and allows a look insight the complete system. Another outcome has to be the image processing application at the base station which has to collaborate with the simulation.

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