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Wireless Ranging in Swarm Robotics

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Wireless Ranging in Swarm Robotics

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The FINken robot platform is used to research intelligent swarm behaviour. To implement such behaviour a new sensor is needed to measure the distance between the FINken quadcopters. The Atmel Ranging Toolbox was used to create a sensor measuring this distance.

After the implementation, the influence of different factors on the system was determined to find out if the sensor could be integrated into the FINken robot. Additionally, it was analysed how well the properties of a distance function apply to the measured range values.

The sensor is not fully suitable for the use in the FINken robots in its current form. However, some strategies to improve the quality of the measured data are developed.

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1 Introduction

1.1 Motivation

The FINken project aims at creating a swarm of autonomously flying quadcopters to research swarm intelligence behaviour on robots. Many algorithms in swarm intelligence are based on distance values. As a consequence it is important to find a sensor that is capable of measuring distances between copters and to integrate it into the FINken robots. An obvious choice for this distance function is measuring the euclidian distance in between the robots.

There are already ranging sensors that are incorporated into the FINken robots. However, those sensors measure the distance to arbitrary objects in the environment. The new sensor should be able to measure the distance to another sensor which is queried by address.

1.2 Requirements

There are basically three requirements for the ranging sensor. Fulfilling these requirements is the goal of this thesis.

1. Interaction between the copter and the ranging modules should be minimal.
2. The ranging nodes need to be integrated into the copter.
3. The values yielded by ranging should be of usable quality.

1.2.1 Interaction between Copter and Ranging

The copter should not influence the function of the ranging modules and vice versa. Using an ultrasonic ranging method might not be feasible as the copter already uses multiple ultrasonic sensors. If no measures are taken to counteract medium access problems, both sensors will disrupt each other until the sensor values of both sensors are completely useless.

This requirement can be mitigated to a certain degree. If there is interaction between copter and ranging sensors, the setup of the quadcopter could be changed to eliminate the interaction. However, the FINken robot is used in research and changing one component usually means almost all components have to be adjusted, as most components are interdependable to some degree.

1.2.2 Integration of the Ranging Modules

In order to be used in the FINken project, the sensors need to be integrated into the robots. This means that the ranging modules need to be lightweight and small enough to fit on a flying robot. Additionally, there needs to be an interface that can transmit the data from the new sensor to the firmware controlling the robot.

One of the aspects of integration is that the robots should interact locally to form a swarm [21][1]. As a consequence, it is not sufficient to measure the positions of the copters with external sensors and to provide the distance values via telemetry. The robots should rely solely on internal sensors.

1.2.3 Yielding Usefull Values

Yielding usefull values seems to be a trivial requirement, but is actually the hardest of all three. The area of operation for the FINken robots is only 3 m wide and 4 m long so the range measurements need to be sufficiently accurate for those small distances.

It is desireable that the range measurements fulfill the properties of a distance function.

Additionally, the update frequency needs to be high enough to support the great accelarations and velocities of the FINken robots.

[1] In contrast to a multi agent system that would rely on a common knowledge base.

1.3 The FINken Robot Platform

The goal of the FINken project is to implement intelligent swarm behaviour on flying robots and to research how swarm collaboration performs in a real world application. The robots need to fly in an stable manner on their own and be capable of interacting with other other. Nevertheless, they must not disrupt the other swarm members. Those robots should perform given tasks defined to encourage swarm based interaction. Their behaviour can be evaluated and compared to the theoretical models developed by swarm intelligence research.

1.3.1 Robot Description

The robots are propelled by four rotors that are driven by brushless motors. The quadcopter is rotated around pitch, roll and yaw axis by controlling the motors. Additionally, the overall amount of thrust can be changed. The airframe houses all the actuators, processors and batteries needed for flight. It carries a multitude of sensors used for operating autonomously and interacting with other robots and the environment.

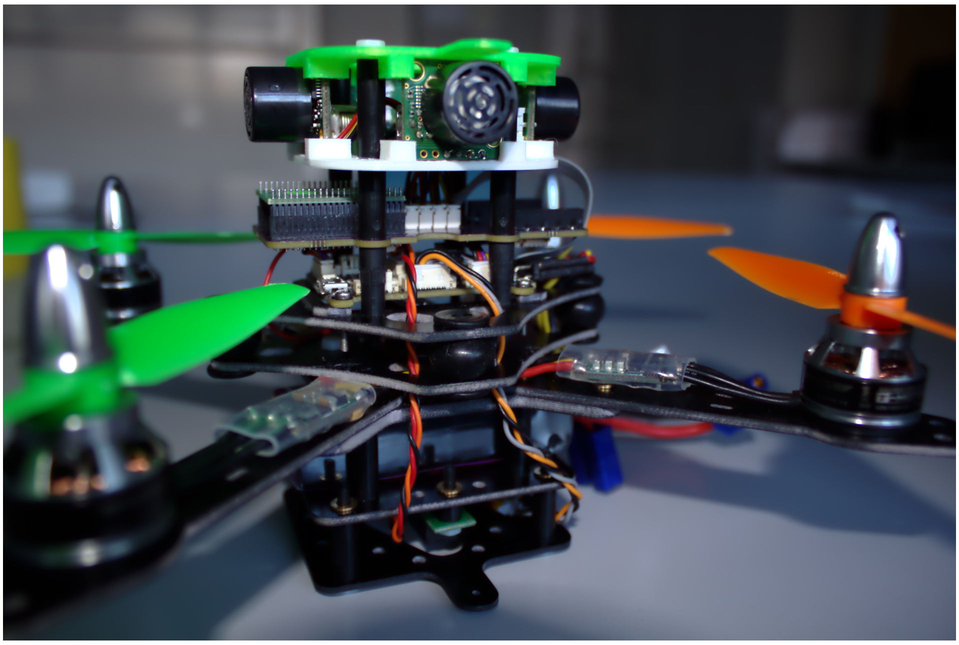

Figure 1.1: The FINken robot, revision 3

The robots are capable of highly dynamic flight maneuvers—the robots have enough acceleration to leave the operating environment in any possible direction in less than one second. This is mainly because the robots need lots of payload capacity to carry different sensors. However, highly dynamic behaviour is not usefull for our research. The high power of the motors can also be used to better stabilise the copter, which is needed for the FINken research.

The FINken robot needs to be controlled very accurately. If the copter is angled by only $3°$ and its height is kept stable, it is accelerating at about $1\,\mathrm{m\,s^{-2}}$. The copter reaches a velocity of over $1\,\mathrm{m\,s^{-1}}$ when travelling through the arena at this small angle. The example illustrates why the algorithms controlling the copter are susceptible, even to small calibration offsets in pitch and roll angle.

1.3.2 Environment

The FINken project is focused solely on indoor application. Special characteristics of indoor flight are the following:

- The area of operation is small and enclosed.
- Some sensors[2] that are typically used in quadcopters are not suited for indoor use.
- Velocities are much lower.
- Miniaturisation becomes a necessity.
- Humans need to be protected from the quadcopters.

In the swarmlab the quadcopters fly in an enclosed arena. It is designed to protect the robots from mechanical damage. Furthermore, it will not disrupt the function of the sensors the robot is using.

The FINken robots fly in an area of 2 m by 3 m that can be expanded to about 3 m by 4 m. The flight area is enclosed by netting and ultrasound-reflecting foil. Those barriers act the same way a wall would do, without damaging the robots if they fail to elude them. Usually, the altitude of operation is between 0.4 m to 1 m. To prevent damage when the quadcopters crash, the floor is covered with mats that work well with ultrasound and infrared sensors used by the FINken.

[2] In particular GPS, magnetometer and barometer.

Additionally, a projector creates artifical environmental factors for the robots by projecting an image into the arena. The colour at the current position can be measured by an rgb-sensor mounted on top of the robots. Certain tasks may be assigned to the robots to interact with this environment, for example finding the brightest spot. The advantage of this method is that this environment is easy reproduce and change.

1.3.3 Sensor Concept

The sensors used by the FINken robots serve two purposes: To enable the robots to fly autonomously and to interact with other robots and the environment.

The robots need to function as single individuals to form a swarm. That means not crashing into walls, ceiling, floor or other robots. The sensors needed to achieve this behaviour are more important than the other sensors of the quadcopter.

Not crashing breaks down into two major problems: Height control and navigating the x-y-plane without colliding with other physical objects.

Height Control

To control the height of the copter a sensor is needed that is able to measure the current altitude. Two sensors are capable of this measurement: The IR-sensor and the optical flow sensor[3]. Each of these sensors is sufficient for height control on its own, usually only one of both sensors is installed.

Detecting Physical Objects

To detect physical objects in its vicinity the FINken is equipped with four ultrasonic distance sensors. With those sensors objects cannot be differentiated. The nearest object in the direction of perception is sensed.

The ultrasonic sensors allow the robot to evade walls and other obstacles by keeping a safe distance.

[3]The actual height measurement is made by an ultrasonic distance sensor that is one compontent of the optical flow sensor

Interaction With Other Quadcopters

The ultrasound sensors are also used to avoid collsions with other quadcopters. Additionally, the new ranging sensor can be utilised to allow more complex interactions between copters as the range sensors can distinguish between the copters and other ranging nodes.

Measuring Speed

With both height control and wall avoidance the FINken are capable of flying for long time periods. This works as long as the velocity of the robot is small enough so it is able to react to obstacles in time. The optical flow sensor is currently utilised to restrict the movement speed of the copter. This is another possible field of application for the range sensors.

In the small operating area in the swarmlab the velocities are usually not exceeded. For this reason the optical flow sensor is not mandatory.

Interaction With a Virtual Environment

To research interaction with an artifical environment as described in subsection 1.3.2 the quadcopters are equipped with a colour-sensor. Similarly the ranging sensor can be used to create virtual points of interest that can be sensed by the robots.

Orientation

The quadcopters only navigate based on their current perception, in particular by following the walls. Range measurements may be used for more sophisticated orientation strategies. The copters could navigate by following beacons in the environment or by computing a position estimate.

1.3.4 Hardware Description

There are different ranging technologies that might be used in a FINken quadcopter. However, different components can interfere with the new sensor.

Part	Description
Frame	The frame is made of GFK material and plastic, rotor to rotor distance is 10 cm
Propellers	The FINken use 5”x3” propellers
Motors	Four brushless motors that may cause RF-interference and noise
Power-Supply	Lithium polymer batteries with nominally 11.1 V output voltage that is converted to 5V and 3.3V by the power distribution hardware
Sonar Sensors	Sonar sensors to measure the distances to the nearest object in four directions (front, back, left, right)
Optical Flow	PX4 optical flow sensor to measure x- and y- velocity and distance to ground
IR-Sensor	IR-distance sensor measuring distance to ground, alternativ to optical flow sensor
Telemetry	BTLE-/Zigbee modules to exchange data with the ground station
RC	2.4GHz based radio control to manually control the robots
Autopilot	Lisa/MX version 2.1 [2] running the paparazzi [3] autopilot firmware.

Table 1.1: Hardware Components of the FIKen 3 Robots

1.4 Evaluation of Existing Ranging Solutions

Keeping the requirements from section 1.2 in mind, there are some technologies that can be used for ranging. The usual application for most of those technologies in research is positioning, which makes it difficult to find comparable numbers for ranging-only applications. In positioning usually more than four range measurements are combined to compute one position. By doing so ranging errors are mitigated to some degree. When only doing ranging this method of error mitigation is not available.

It is still interesting to search for positioning applications, since many of those positioning technologies are based on multilateration[4]. [4]

[4] The usual methods for positioning are: *multilateral*—which is relevant for this work, because only ranging measurments are used. *Multiangular*—where angle measurements are used and *orientating in a map* with different factors like beacon-positions.

1.4.1 Optical Tracking

Many projects use external optical tracking to measure the position and orientation of the quadcopters. The most common optical tracking systems are very costly in comparison to the other ranging methods described here. The most affordable solution from Optitrack able to track five targets at once costs more then 10 000 $ [19]. The price is justified by the superior performance of this method. Optical tracking can be highly accurate at a very high update frequency. The motion capture system in the flying machine arena [1] captures images at 200 frames per second. In addition to the position of the quadcopters, motion capture systems are able to measure the orientation of the quadcopters.

Even a tracking system that is more cost efficient such as the one developed by Achtelik et al[5] is not an appropriate solution for the FINken project. A tracking system provides information that is gathered for the entire operating area and afterwards broadcasted to the robots. The big advantage of swarm behaviour would be lost. No common information base is required in order to form a functioning swarm.

As such external tracking could be a valuable tool for observing the swarm behaviour. However, it is not meeting the requirements for the sensor the robots should use (see subsection 1.2.2).

1.4.2 Indoor Time of Flight

An obvious approach for replacing the GPS signal is to use a similar approach indoors.

The problem is that very short timespans have to be measured accurately, because radio waves travel at the speed of light. Lanzisera, Lin and Pister [16] state that standard errors of 2.6 $\mathrm{m_{RMS}}$ and 1.8 $\mathrm{m_{RMS}}$ were measured in different indoor scenarios. With an operating area only 3 m wide this solution is not suited for the robots.

A more promising project is DecaWave. According to Kempke, Pannuto and Dutta [14] the measurement error is generally less than 1 m and with filtering can be brought to below 15 cm. Mahfouz et al[18] even claims that an accuracy of 10 cm can be achieved. Additionally, the DecaWave modules are able to transmit the telemetry with high data rates on top of performing ranging [10]. While the DecaWave modules seem like suitable ranging sensors for the FINken the hardware was not available to the FINken project at the time.

1.4.3 Ultrasonic Time of Flight Ranging

A very clever approach to ranging is used by ranging solutions like cricket [22] and active bat [24]. RF-Signals travel at the speed of light and therefore very short time-periods need to be measured accurately to compute distances from time of flight. Sound however travels at a speed much slower than radio waves so the time periods that need to be measured are much longer. Unfortunately the slower propagation speed causes a different problem.

When using sound as medium there is an upper bound to the update frequency for all nodes sharing the medium. Woodman and Harle [24] claim that one ranging measurement can be done in a 20 ms time slot. As a result, there can be up to 50 range updates per second. A swarm of five robots that form a fully connected graph would need at least ten range measurements to obtain all swarm distances. So the upper boundary for ranging update frequency in this swarm of five robots is 5 Hz. Considering that this is not the actual performance but the upper limit, this is a solid disadvantage of this method.

Currently the FINken robots use sonar based distance sensors to measure the distance to the nearby objects. It is highly unlikely that those distance sensors and an ultrasonic ranging method can be used in parallel without disrupting each other. This problem could only be solved by implementing some kind of medium access control protocol By doing so the maximum update frequencys for both sensors would be reduced.

In conclusion, ultrasound based ranging is a very neat approach to ranging that is already used in other quadcopter projects [11]. Still integrating an ultrasonic ranging sensor into the FINken is impractical, because other ultrasound sensors are already in use.

1.4.4 Signal Strength

A property that can be used to do RF-based ranging is signal strength. The further the source of the signal is away the weaker the signal gets. RSSI[5]-based ranging is done for serveral different wireless technologies: Bluetooth[20], WLAN[13, 17], RFID[12].

There are serveral drawbacks to RSSI based ranging. Zanca [25] writes: "Unfortunately, the indoor radio channel is very unpredictable, since reflections of the signal against walls, floor and ceiling may result in severe multi–path interference at the receiving antenna.". Furthermore, no antenna will transmit radio waves equally in every direction–especially if it is mounted on a robot containing lots of wiring.

Ultimately, the orientaion and location of the quadcopter might have a bigger impact on the RSSI value than the actual range has. Thus an RSSI based ranging method will probably not yield sufficient results.

1.4.5 Phase Difference

Another property that can be measured and used for ranging is phase shift [15]. This is utilised by the Ranging Toolbox from Atmel. Multiple frequencys are used to measure the phase difference of the signal. As the wave length changes with different frequencys a distance can be computed from all of the measured phase differences [8]. Similar hardware using the same software stack is sold by *Dresden Elektronik* and *Meterionic*.

Using phase differences in radio waves mitigates the medium access problems of ultrasonic methods as well as the wave propagation problems of RSSI-based methods.

Therefore, it seems like a feasible approach for the FINken robots.

[5]Received Signal Strength Indicator

Method	Interference expected	Update Frequency	Accuracy	
Optical Tracking	No	Very High	Very High	external
RSSI	No	High	Very Low	internal
Ultrasonic Ranging	Yes	Low	High	internal
Time of Flight	No	High	High	internal
Phase Difference	No	High	High	internal

Table 1.2: Comparison of Ranging Methods

2 Integration Concept

As stated in section 1.2 the sensors should be integrated into the FINken robot in a way that is does not disrupt the normal operation of the FINken robots. In order to do so, a version of the hardware has to be chosen that is not to big and heavy for a flying robot. Additionally, an interface to the autopilot board has to be found that integrates well into the existing infrastructure.

2.1 Hardware

2.1.1 Ranging Hardware

There are several different possible hardware plattforms for the Atmel ranging software. Using the firmware of the Atmel Ranging Toolbox [6] for the REB233SMAD Evaluation Kit [7] was the only setup that was already supporting ranging at the time this thesis started.

For evaluation those modules are quite usable, but there are better options available for use in the real application, as the sensors from the evaluation kit are quite big and heavy. It is planned to use the 802.15.4 modules from dresden elektronik which are already integrated into the new hardware revision of the FINken robots as telemetrie transmitter. Another way to integrate this approach to ranging into the FINken robots is to miniaturise the REB233SMAD-modules, by leaving unused PCB-area and connectors. This can be done by using the ATZB-X0-256-3-0-C ZigBit [9] modules, that use the same radio module and processor as the REB233SMAD-kits.

In conclusion, the dresden elektronik modules are best suited for the copters. If it becomes apparent that those modules are not capable of ranging it would still be possible to create a miniaturised version of the Atmel sensors. As seen in subsection 4.2.1 using another frequency might cause a huge improvement in ranging quality. This is especially true if the modules can be used for ranging and transmitting telemetry at the same time.

2.1.2 Assembly

As it is unclear which version of the ranging hardware is best suited for the FINken robots there are several ways to fasten the ranging modules.

If a module from dresden elektronik is used it can simply be plugged into the pin header currently used for the telemetry module. If a new PCB is used it can be mounted using the fixed hole spacing of 30.5 mm that is used by a lot of quadcopter hardware components.

Maybe an extra mounting method is needed for the antenna. The best place for the antenna is probably on top of the sensor tower to lower interference with the other components of the copter.

2.2 Software Architecture

The FINken robots are controlled by a micro controller handling all the computation needed. There is no distinction between higher level logic like pathplanning and low level code as the stabilisation of the copter in terms of hardware. The exact board that is used is the LISA/MX autopilot board in hardware revision 2.1 [2] which runs the paparazzi autopilot firmware [3]. The paparazzi framework provides an easy way to implement new hardware drivers for all devices that are connected to the board via several interfaces.

Figure 2.1: Information Flow in the FINken Robots. All software components of the the autopilot board are shown in green. Sensor hardware is shown in orange and actuator hardware is shown in yellow.

An important design decision is how to divide the process of ranging and filtering the results between autopilot and sensor node. The sensor could yield its raw values to the master device and be done. This allows to implement fine tuned and application specific filtering. However, this also means that there is no convenient way of obtaining reasonable values that are already filtered. Another factor that influences this decision is the processing power of the sensor nodes. Running filters on the sensor node might deallocate valuable processing power and memory in the master device.

As the FINken robots autopilot is quite well resourced and the measurements are probably not good enough to be used without sophisticated filtering the raw values of the sensors are transmitted.

However, it may still be reasonable to provide higher level data computed by the sensor nodes later on. Position estimation is an application that needs a lot of computation and memory. Additionally, computing position estimates will be similiar accross different applications of the ranging modules. The position estimate might also be used as a direct input to filters that use additional information directly, especially if the computation of the position does not cause a delay in the sensor data.

2.3 Interconnect

All components of the FINken communicate directly with the autopilot board as can be seen in section 2.3. The new sensor should be connected to the autopilot as well.

There are different methods to achieve this. In Table 2.1 all the interfaces supported by the LISA/MX board and the connected devices are listed. One of those interfaces will be used for the new sensor.

2.3.1 Pulse Width Modulation / Analog Value

Using a single GPIO pin or analog value is completely impractical, but a good example to explain the problems the honest solutions needs to address.

First of all, there is a limited number of GPIO or ADC-pins on both boards. On the autopilot board those pins are quite rare, especially because they cannot be shared easily between components. The second problem is that not only a range value needs to be read from the sensor, but it is neccessary to tell

Available	Used	Type	Conneceted Hardware
4	2	Analog Pin	IR-Sensor Battery Voltage
4	3	UART	Telemetry RC-Reciever Optical Flow Sensor
8	4	PWM Output	4 Motorcontrollers
2	1	I2C	Ultrasound Sensors
			Colour Sensor
1	0	CAN	—

Table 2.1: FINken 3—Hardware Ports and Usage

the sensor which value to fetch. Therefore, some kind of bidirectional communication between autopilot and sensor needs to take place. The big advantage of using a GPIO pin would be that only one single wire[1] would be needed to connect autopilot and sensor.

2.3.2 UART

The "Universal Asynchronous Receiver/Transmitter"-Protocol uses two wires to establish communication between devices. [23]

A disadvantage of the UART protocol is that it is a point-to-point connection. It is not possible to connect multiple slave devices to one UART port of the master device. On the Lisa/MX autopilot there are four dedicated UART connections that might be used, but already three of them are in use.

Additionally, UART is a character based communication protocol. As there is no detection for bit errors and no framing, sophisticated protocol design would be a neccesity for implementation.

[1] Two additional wires are needed to supply the sensor with power, those wires will be needed regardless of the communication protocol.

2.3.3 SPI

In contrast to UART, SPI does framing and is more suitable. Serial Peripheral Interface is a four wired bus that also allows bidirectional communication. There are two modes of operation that can be used in SPI. In the independant slave configuration a single IO-pin defines which of the slaves is currently active. As the LisaMX only has one chip select pin this mode is not really interesting to be used by the sensor nodes.

The daisy-chain-configuration uses the chip select pin to pass all data along the modules and works much like a shift register. The other applications planned for the SPI port are communication with a high level processor and fast data logging to a micro SD-card that will need a lot of bandwith. This means the sensor would need to be capable of high clock speeds and data rates in order to ensure that the neccessary bandwith is available for the other applications.

2.3.4 CAN bus

Controller Area Network is a bus protocol mainly known for its applications in the automotive industry. CAN is an option available on the paparazzi board, however, implementation on the sensor side would mean a lot of effort compared to the other communication protocols. Additional hardware would be needed as well.

2.3.5 I2C

I2C is a two wired bus protocol that can be used to connect multiple slave devices to one master device. As every communication in I2C is directed to the devices via an address it is quite simple to connect new devices in a star configuration simply by attaching it to the two wires of the bus. There are already multiple sensors connected to the autopilot via I2C. All of the ultrasound-sensors and also the colour-sensor use I2C to communicate with the autopilot. This also means that there is already know how and working code that can be utilised to connect the new sensors.

One of the disadvantages of I2C is that misbehaving slave devices can disrupt the communication of all devices on the bus. The autopilot board supports to have two independant I2C-networks which makes it possible to separate critical and non-critical devices which helps to mitigate this problem.

Especially the fact that there already is a I2C sensor network on the FINken makes I2C the best choice as a communication protocol for the new sensor.

2.3.6 Findings

It is possible to integrate the ranging nodes into the FINken robot. I2C is the protocol best suited for communication with the autopilot.

For an application in the robots a miniaturised version of the module is needed.

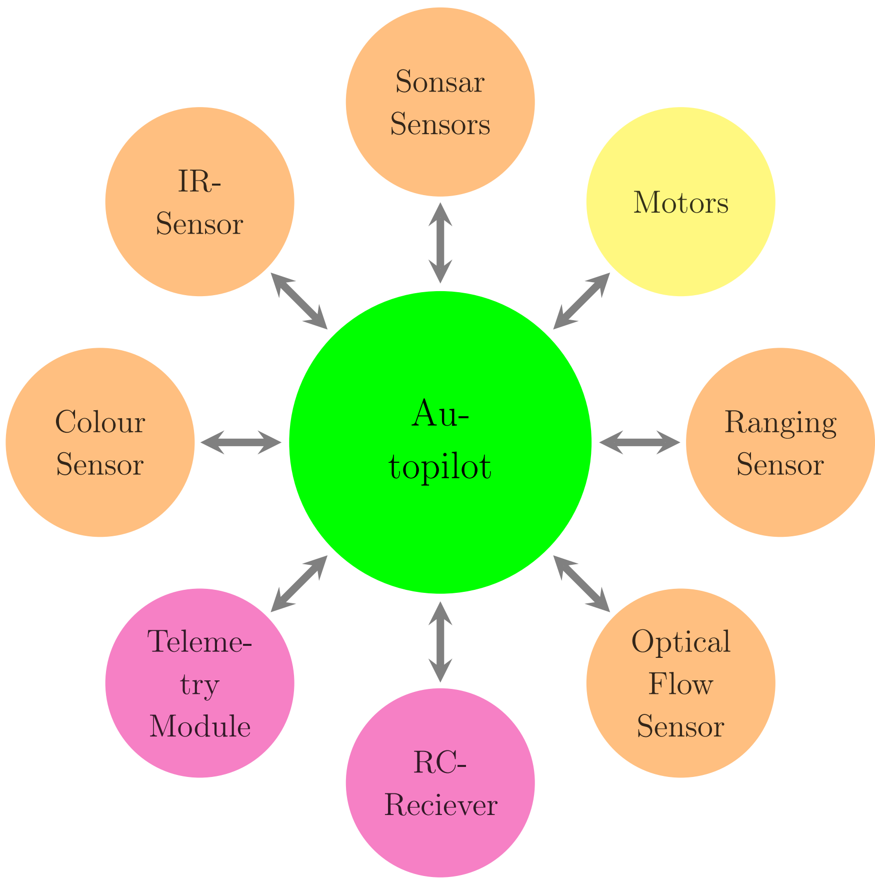

Figure 2.2: Onboard Communication of the FINken Quadcopters. All sensor and actuator hardware is directly communicating with the autopilot board.
Sensors are showed in orange, actuators in yellow and radio links in magenta.

3 Implementation

The basic idea for the firmware of the nodes is to provide an I2C interface to initiate measurements and read values. Additionally, the settings of the modules can be changed by the same interface.

3.1 Description of the Ranging Process

While the ranging itself is treated as a black box in this thesis, it is still needed to konw how a measurement is executed. For ranging there are three functions a node can fulfill. The *reflector* is the target node of the range measurement. The *initiator* is the node sending the original signal and measuring the actual phase difference of the reflected signal. The measured range will be the distance between initator- and reflector node. The third node type is only needed for remote ranging. The *coordinater* node is used to trigger a range reading between two other ranging nodes.

Each of the ranging nodes is able to act as an initiator, coordinator and reflector without changing the firmware. If the nodes are configured correctly the nodes communicate about the pending measurement on a seperated RF-channel and executed it afterwards.

The measuring a range value works as follows:

1. set initiator and reflector node
2. start measurement
3. wait for measurement to finish
4. fetch the result

As result of the ranging process two values are returned: Range and DQF. The range value is the estimated range in cm. The DQF is an additional parameter which tells the user how accurate the range value is assumed to be.

3.2 Communication Interface

3.2.1 I2C Registers

The sensor has different functions available as I2C-registers. The master device writes one byte to the register followed by arguments for the different functions. Either the sensor node answers with an acknowledge byte or the return value of the request. All the implemented registers are listed in Table 3.1. In normal operation the master device will set reflector and initiator address, initiate the ranging and request the resulting range value afterwards. This is achieved with the START_RANGING and READ_LAST_RANGING commands.

Additionally, some basic configuration can be made via the I2C interface.

There are two types of address used by the ranging nodes, both can be set via the I2C interface. The I2C-address is the address of the I2C-device, that needs to be changed to avoid address collisions that will occur when multiple ranging nodes are used with one master device. The short address is the address used for ranging. It is independent from the I2C address in order to allow multiple ranging nodes on one I2C master device as well as using ranging devices with equal I2C-addresses on multiple devices.

The FINken robots will certainly the same I2C address for the ranging nodes and use the aircraft-ID of the FINken as short address. As the aircraft-ID of the FINken is only one byte long the higher byte of the ranging short addresses might be used to distinguish between other robots in the swarm and nodes in the environment.

Initiator and reflector address refer to the short addresses of the nodes on both ends of one measurement. As the nodes are capable of remote ranging the initiator might be a different node than the one connected via I2C. In particular this means that remote range readings can be taken without the need of additional communication.

3.2.2 Datafields in the Ranging Result

Table 3.2 describes how the data structure for transmitting range values is organized. The reason why so many fields are included into the range measurement is that the master device most propably needs to do filtering based

Byte	Name	Description
0x0	ECHO	return payload byte
0x1	START_RANGING	trigger range measurement
0x3	START_REMOTE_RANGING	trigger remote measurement
0x2	READ_LAST_RANGING	read measured distance
0xFE	SET_I2C_ADDRESS	set new I2C address
0xFD	SET_SHORT_ADDRESS	set new ranging short address
0xFC	SET_REFLECTOR_ADDRESS	set reflector address
0xFB	SET_INITIATOR_ADDRESS	set initiator address
0xED	GET_SHORT_ADDRESS	get ranging address
0xEC	GET_REFLECTOR_ADDRESS	get reflector address
0xEB	GET_INITIATOR_ADDRESS	get initiator address
0xFF	CLEAR_BUFFER	clear I2C write buffer
0xCA	SET_FREQ_START	set lower ranging frequency
0xCB	SET_FREQ_STEP	set ranging frequency spacing
0xCC	SET_FREQ_STOP	set upper frequency
0xCD	SET_DIVERSITY	turn on/off antenna diversity

Table 3.1: Implemented I2C-Commands and Description.

on status and dqf-values. The addresses of the initator- and reflector node are included to match measurements in case one of the packets is lost or a new measurement is completed before the old value is read.

The data type for the range values is changed, to not block the I2C-device unnecessarily. Instead of the original 32-Bit value only a 16-Bit value is used, as distances up to more than 60 m are will never occur in our application.

Type	Name	Description
uint8_t	status	status of the range measurement
uint8_t	dqf	quality of the range reading
uint16_t	distance	measured distance
uint16_t	short_addr1	initiator address
uint16_t	short_addr2	reflector address

Table 3.2: Fields included in one range measurement

3.3 Python Scripts

For testing the sensor nodes and collecting sample data a raspberryPi mini-computer was set up as an I2C master device. The scripting language python was used to implement all the functions the I2C interface of the ranging nodes provides.

i2cranging.py contains functions for the master side of I2C communication. Those can either be used from the python REPL or by other scripts. *poll_range.py* is a convenient program to gather range readings continously from the unix shell and is mainly used to generate csv-files. Those csv-files are used for evaluating the ranging nodes.

Gathering data with those scripts may not only prove useful for this work. It could be an efficient approach to develop and evaluate algorithms for filtering and position estimation using higher level concepts. By implementing only those algorithms on the embedded devices that prove to be useful a lot of implementation effort can be saved.

4 Evaluation

The REB233SMAD-kits fulfill the first two requirements set for the ranging sensors. However, the quality of the data is the most important factor for the usefulness of the ranging nodes in the FINken project[1].

The evaluation of the sensors is made difficult by the fact, that there are many interdependend variables that influence each other in unclear ways. The ranging process itself can only be treated as a black box until the range value is returned by the ranging API of the Atmel RTB firmware. Especially the effects of RF-noise and multipath propagation are environmental influences that are not controllable and hard to measure. Nevertheless, they still have great influence on ranging quality.

4.1 Robustness of Implementation

Not only the quality of the measurements is relevant for use in the FINken robots. The sensor also needs to be well integrated into the autopilot framework.

With the current hardware this integration cannot be done completely, because the current hardware plattform is simply to big to fly. However, the software is already stable enough to be used in a real life scenario.

4.1.1 Bus hangup

I2C is an easy to implement and use bus protocol. One of the drawbacks of I2C is that misbehaving clients are able to block the whole bus. As a consequence,

[1]see subsection 1.2.3

a malfunctioning sensor might render all others sensors useless, in the worst case the copter crashes.

At the moment the ranging sensors cause bus hangups if range readings are requested too often. However, if this query rate was not exceeded, the sensor bus has been working for many days without errors.

4.1.2 Missing Sensor Values

Another problem that may occur is that I2C data packets can get lost. As a consequence, the autopilot has to rely on expired data. This breaks any kind of derivate computed from the range value.

If there is unplanned latency in the sensor values, the control algorithms implemented may not be able to stabilise the system any more.

Those errors did not happen in the test setup as long as no error condition was provoked (i.e. by wrong wiring or exceeding the query rate).

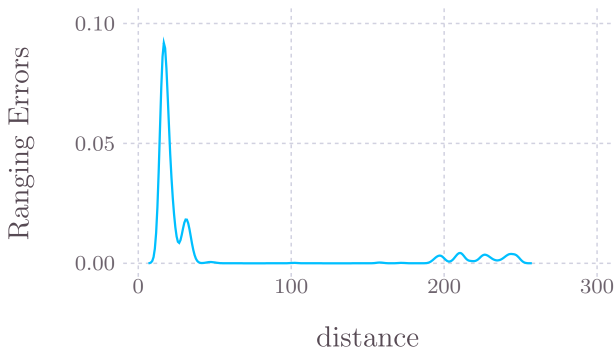

Figure 4.1: Missing Values vs. Distance (cm).

However, the ranging algorithm itself can provide range measurements with a DQF value of zero. This means the measured range value should not be used.

These errors are very rare as long as only small amounts of RF interference are present. In the nightshift-dataset less than 5 % of the values where rejected because the measured value was impossibly high($> 5m$) or the DQF value was zero.

In Figure 4.1 it can be seen that those errors mostly happen when the two nodes are very close to each other. As the quadcopters cause a lot of turbulence a much bigger safety margin will be needed to avoid collisions. Hence the distance where most measurements fail will be uncommon in real life application.

4.2 Ranging Accuracy

The most important question for the FINken project is: “Can the ranging values be used by the FINken robots?”. To answer this question some understanding of the magnitude and distribution of the ranging error is needed.

Finding out how accurate the range values actually are proves rather difficult, as there are lots of interdependend variables that influence ranging accuracy.

Noticable disruptive effects are:

- multipath effects
- supplied voltage
- RF-noise
- antenna characteristics
- chosen frequency

To get meaningful and reproducable measurement results these effects need to be minimised or be constant over the course of the measurements. The same antennas where used throughout all measurements and the frequency range was selected prior to the measurements used in this evaluation.

4.2.1 Frequency Selection

The frequencies used by the ranging can be chosen by the user, however frequency selection greatly influences the quality of the measurements. This is especially true, as normal 2.4 GHz wifi and serveral other technologies are using the same frequencies as the ranging modules the selection of a well working one is crucial to ranging performance. In subsection 4.2.1 there is an analysis on the frequency utilization on wifi channel 6. A download was started and then ended which is noticable in the waterfall plot.

Comparing the utilisation on this channel with the frequency range shown in Figure 4.2.1 which is right next to the first frequency used by the ranging modules several aspects can be noticed. The noise in the frequency range for ranging is much lower then on frequencies with used for wifi—about 15 dB in average and 20 dB in peak. You can also see the peak generated by the ranging modules. The line at the center frequency 2.4831 GHz is an artifact created by the SDR that was used, but the line at 2.483 GHz is created by the ranging modules (which is exactly why the center frequency was chosen right next to the actual frequency).

Because of the lower utilisation of those frequencies a range of 2.480 GHz to 2.500 GHz has been chosen. All the frequencies in this range look quite similar to the sample taken at Figure 4.2.1. This values have to be taken with a grain of salt. It is really hard to reproduce what kind of RF-noise interfering with the nodes is currently generated in the swarmlab.

There are other factors impacting measurement quality that cannot be quantified easily. At least the performance of the antennas at different frequencies cannot be directly measured in our lab. The number of available channels in the frequency range and channel spacing are other variables that might influence ranging quality[2].

In the end this means finding the right parameters for ranging frequency settings is a really hard problem, especially because measuring the ranging error for many frequencies takes a lot of labtime. It is not viable to measure all available combinations for those parameters.

[2] The sourcecode and algorithms used by the modules is closed source, so we are not able to infere the effect of channel spacing and number of channels from that.

Figure 4.2: RF-Spectrum on 2.437 GHz

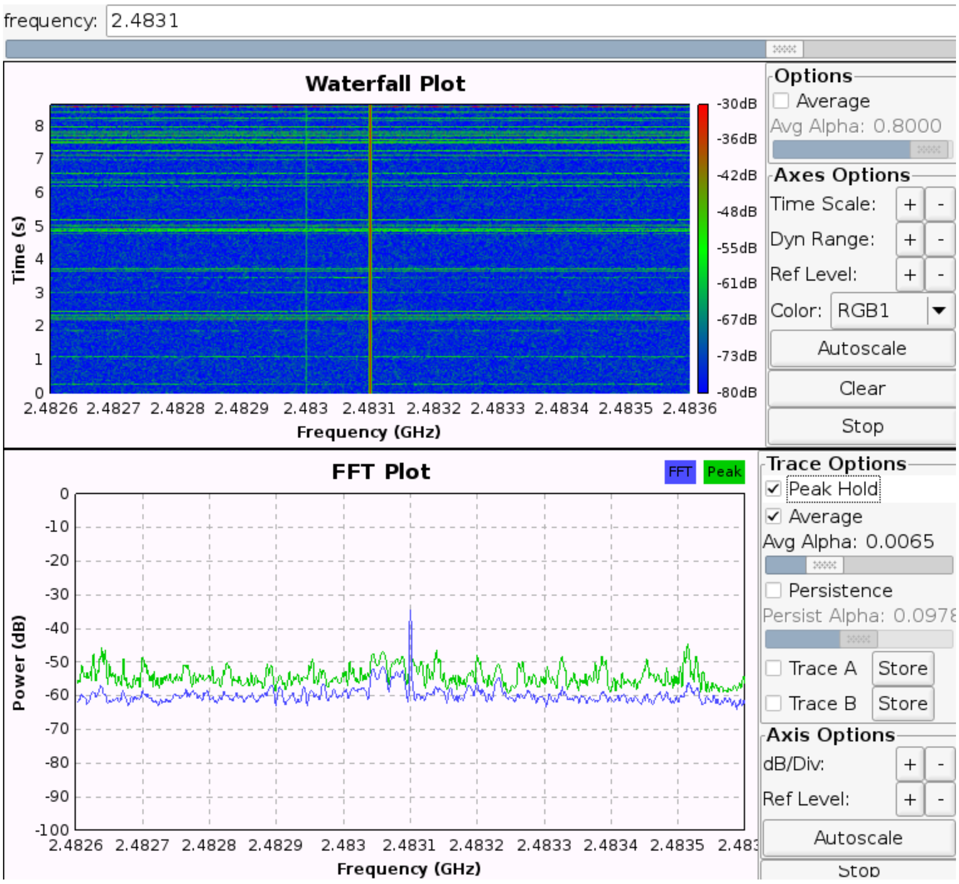

Figure 4.3: RF-Spectrum on 2.483 GHz

Even with the selected frequencies the measurement is only really working when the lab is empty, as basically every person in the faculty uses devices that use the 2.4 GHz frequency range. To create a useful evaluation all the following measurements have been made with an empty lab. Therefore, the measurements were made at night. However, this problem must be addressed before the sensors can be used in a real world application. This is especially true, as the remote control is causing the worst interference with the ranging nodes observed so far and the quadcopters will not work without the remote control.

There are two possible solutions to the general problem: Either the noise in the environment needs to be reduced or the ranging nodes need to use different frequencies.

4.2.2 Measurement Setup

All the following evaluation is done by analysing the data gathered by the ranging nodes. However, the measurements are done in a very specific manner to improve the quality of the measured data.

- the nodes are lifted from the table to minimise multipath effects
- a stable 3.3V input voltage is provided by different voltage regulators, the battery slots are not used
- antennas are always used in the same orientation
- measurements are not taken in the working hours of the faculty (mostly deep at night) when the least ammount of RF interference by 2.4 GHz devices can be expected

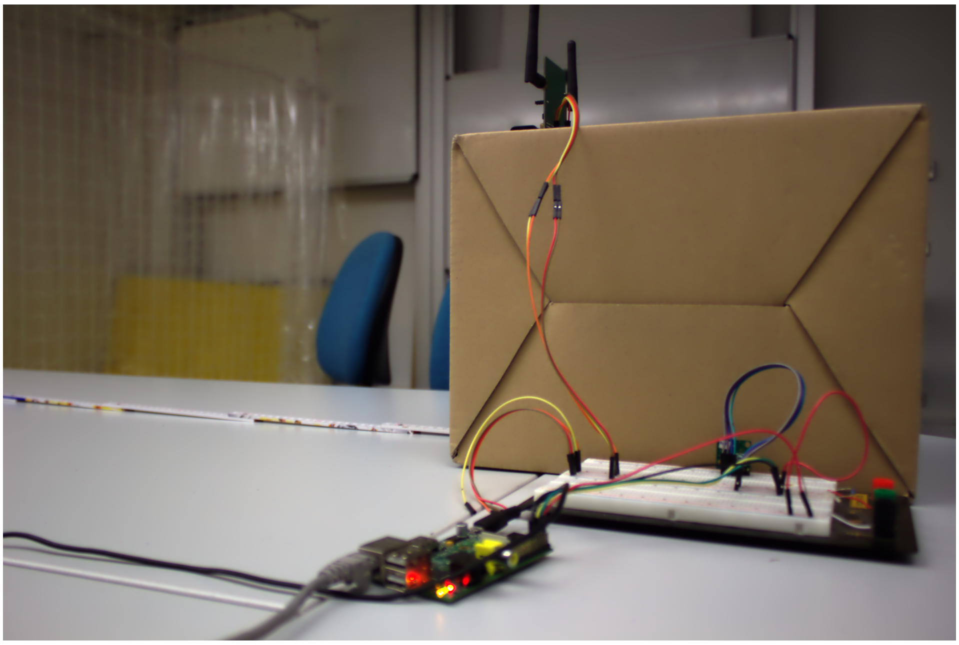

Figure 4.4: Measurement Setup. RaspberryPi microcomputer is connected to the ranging node via I2C.

4.2.3 Data Sets

The evaluation of the ranging nodes relies on three datasets that have been recorded. Before those datasets were recorded many other measurements where made. These measurements are not directly used in the evaluation, but for finding disrupting influences that would compromise the evaluation data.

To avoid confusion the measured range in the dataset is called “range” and the reference measurement for the distance is called “distance”. The same nomenclature can be found in this thesis. All the distance and range values used in the datasets are in *cm*.

“Nightshift”

RF-noise greatly influences the ranging measurements and almost everyone in the faculty uses 2.4 GHz devices. As a consequence, data recorded at night is less noisy than data recorded during daytime. Because of this fact all the data was recorded at nighttime.

The “Nightshift”-dataset consists of range values measured for distances between 16 cm and 250 cm in 2 cm intervals. For each of the distances 200 range values have been measured.

Angle Dataset

To determine the influence of rotation another dataset has been recorded at 50 cm, 100 cm and 150 cm. At each distance one of the sensors was rotated in 30°-steps.

Symmetry

To check if the range measurements are symmetrical the remote measurement capabilities of the ranging nodes where utilized. Three nodes where used to generate more data, while still beeing able to automatically measure at nighttime. It was intended to also evaluate the triangle equation with this data, however this has proven to be impractical.

4.2.4 Relationship between Distance and Measured Range

It is important to know how the ranging nodes behave at different distances. For this analysis the “nightshift”-dataset is used.

	RMSE (cm)	Samples
Nightshift	23.75	23600
Angle	42.74	9597
Symmetry	32.58	17999

Table 4.1: Dataset comparison

In Figure 4.6 for each possible range value an interval is showed in which the real distance is located with a confidence of 90 %. The average size of this interval is 50 cm for all range values smaller than 2 m. It is also notable that the intervals get bigger for greater distances, which may not be suprising. For ranges below 1 m the interval is only 38 cm big, for ranges between 1 m and 2 m the average interval-size is 60 cm.

Another notable fact is that the ideal value (showed as blue line) is always within the intervals.

4.2.5 Influence of DQF on Range Values

One value the ranging api provides is the DQF[3]-value. It is reasonable to expect a huge amount of scatter for lower DQF values. As can be seen in Figure 4.7 this expectation is not met.

Instead, there is a clear relationship between mean error and DQF as showed in Figure 4.8. For low DQF-values the average measurement (< 80) error is negative and for high DQF-values (> 90) positive. As such the DQF-value might be used to improve the range values.

In Figure 4.9 can be seen that this relationship is present at all of the measured distances.

4.2.6 Orientation of Devices

The angle-dataset has been gathered to determine if the angle has an influence on the measured range values. When comparing the datasets it becomes apparent that the squared error in the angle-dataset is much bigger than in the

[3]Data Quality Factor

other datasets. One might believe the higher error stems from the rotation of the devices. This is not the case, as the RMSE is even higher for an angle of zero (51.88 cm), the same angle that was used to record all the other datasets.

There is no clear relationship between angle and error. An explanation for the higher RMSE cannot be provided. Maybe the wiring of the nodes was changing in a way that caused the error while the angle of the nodes was modified. Maybe there was RF-noise even if the measurement was made at night or the changed angle was interacting with multipath effects that where there all along.

4.3 Properties of a Distance Function

The ranging sensor on the FINken robot should be used to provide a distance between two quadcopters, similar to a distance measure used in swarm intelligence algorithms.

If $f(x, y)$ is a distance function it has to have the following properties.

$$f(x, y) \geq 0 \tag{4.1}$$

$$f(x, y) = 0 \iff x = y \tag{4.2}$$

$$f(x, y) = f(y, x) \tag{4.3}$$

$$f(x, z) \leq f(x, y) + f(y, z) \tag{4.4}$$

Of course the value measured by any real sensor will not completely accomplish to satisfy those conditions. For use in swarm robotics it is therefore very interesting to know, in which way the range values violate the properties of a mathematical distance function.

4.3.1 Non-negativity and Coincidence

The first property of a mathematical distance measure to look at is non-negativity. This is quite easy: The values yielded by the ranging modules are positiv. The condition for coincidence is always met as well. Each module has a unique address and is therefore able to check if it is ranging with itself. Having two modules occupy the same physical spot is obviously not possible, so there cannot be two different modules that are equivalent in a mathematical sense.

4.3.2 Symmetry

In this section the following notation will be used: $A \to B$ means a range reading is taken from node A with B as reflector node.

Symmetry is a property that cannot be achieved by the ranging sensors because of noise. A range reading $A \to B$ will not be equal to the reading for $B \to A$ just because the two readings will be altered by noise. The remaining question is: Is the error statistically equal for both directions?

As showed in Figure 4.11 there is clearly an offset between all pairs of range value densities $A \to B$ and $B \to A$. Interestingly the distributions of range values look very similar for each pair densities. This might be due to multipath effects.

However, the lack of symmetry might be utilised.

$$\frac{d(A \to B) + d(B \to A)}{2} \tag{4.5}$$

The remote ranging capability of the nodes can be exploited to gather both values $A \to B$ and $B \to A$ by averaging those values the error can be mitigated.

The new value showed in Equation 4.5 will be symmetric. Additionally, the measurement error will be reduced because of the averaging.

4.3.3 Triangle Inequality

The triangle inequality will be violated by noise. If we measure $d(A, B) + X + d(B, C) + X$ and $d(A, C) + X$ the measurement error X might cause the triangle inequality not to be met.

In Figure 4.12 the density function for one setup of three nodes is showed. The triangle equation is clearly violated as the 200cm distance is underestimated by far. This will happen a lot as there is a lot of noise especially for longer distances.

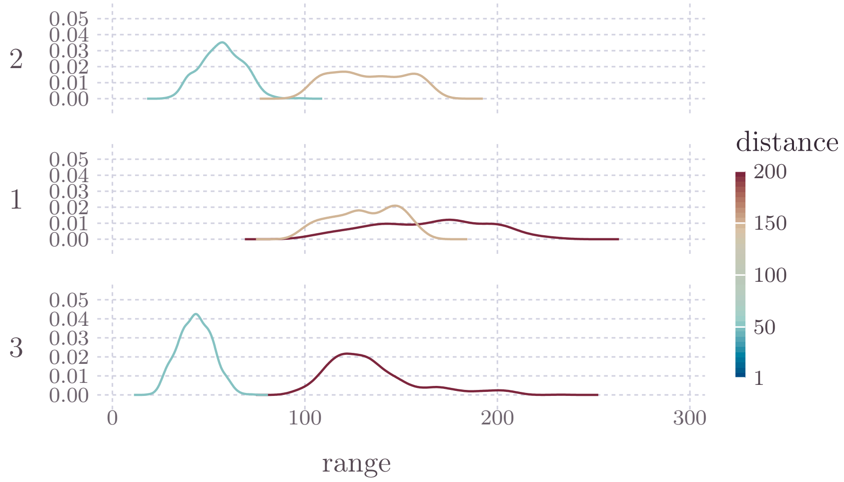

Figure 4.12: Density Functions for 3 Nodes. Nodes were placed in a straight line with numbers 1, 2, 3. Distance 1-2 was 150 cm, distance 2-3 was 50 cm.

4.4 Conclusion

Taking a look at the requirements from section 1.2—will the new sensor be suitable for application in the FINken robots? It is possible to integrate the sensor nodes into the FINken robots, however not in the current hardware setup. The interference of copters and ranging nodes is stronger than expected. RF-Interference disrupts the function the distance sensor. At least the copters do not seem to be disrupted by the ranging nodes. It is still possible to solve this problem by changing the hardware on the copter or the frequency the ranging nodes operate at.

The quality of the range measurements is the important factor showing if the requirements are met. The measured range values are not as good as expected. A filter needs to be implemented to compute usable range estimates. This would introduce a time delay into the measurement which is not desireable.

If the right method of filtering is applied, the sensor nodes can still be useful for the FINken robots.

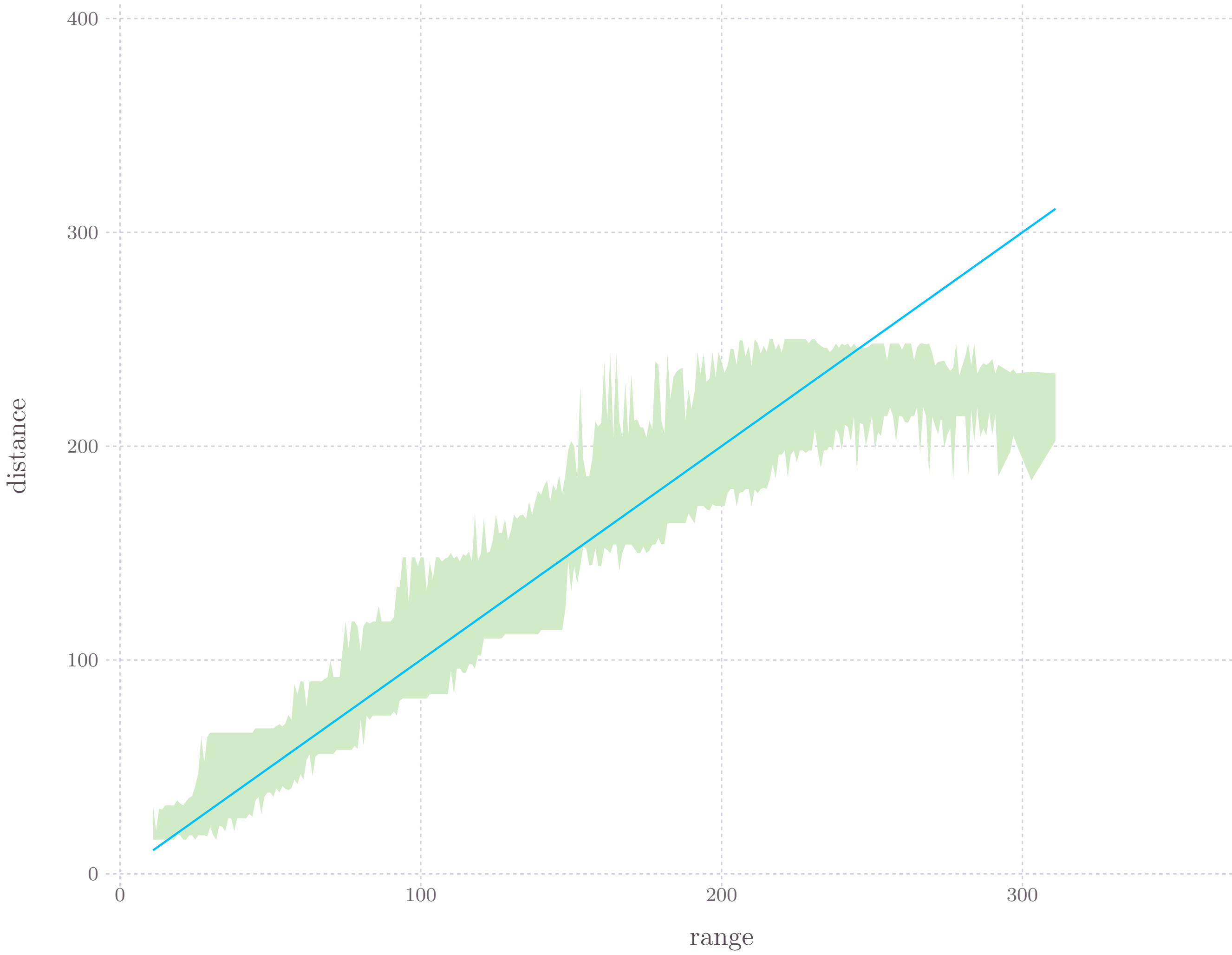

Figure 4.5: Measured range (cm) vs. Real Distance (cm). In this diagram for each possible range value the 0.9-quantile of the real distances are plottet as green area. The blue line shows the ideal value.

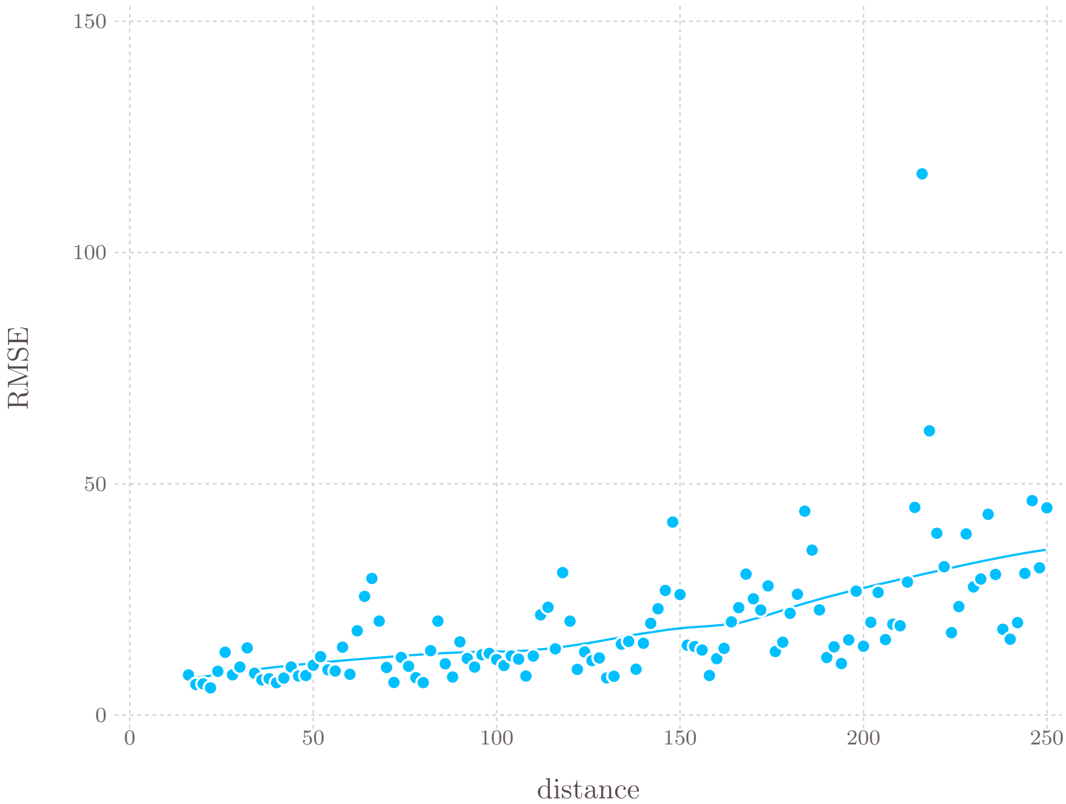

Figure 4.6: RMSE value (cm) for each distance (cm).

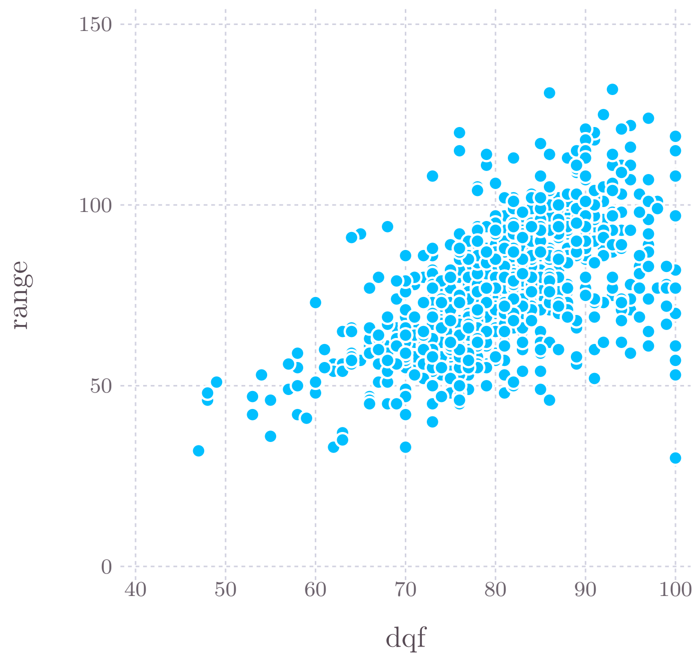

Figure 4.7: 1000 values (cm) measured at 1 m distance

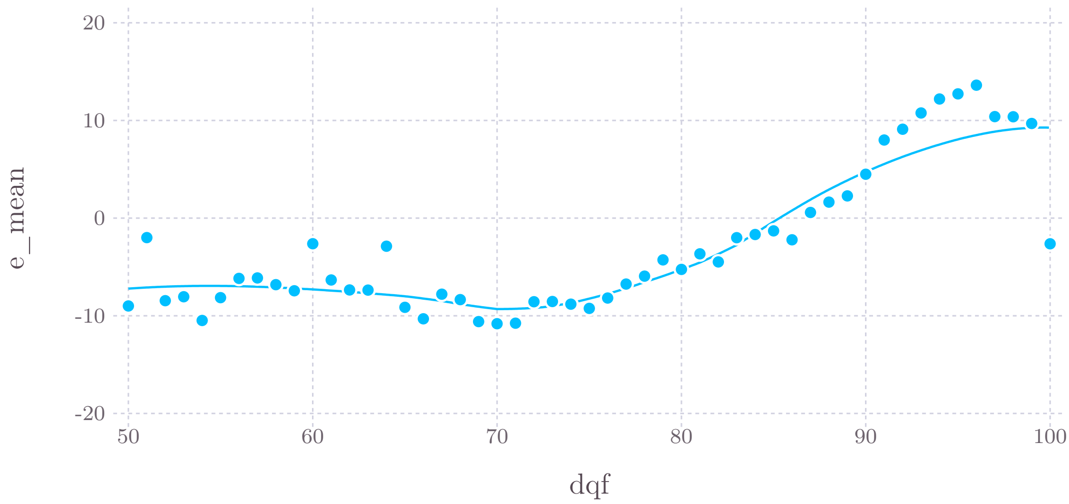

Figure 4.8: Mean Error (cm) by DQF

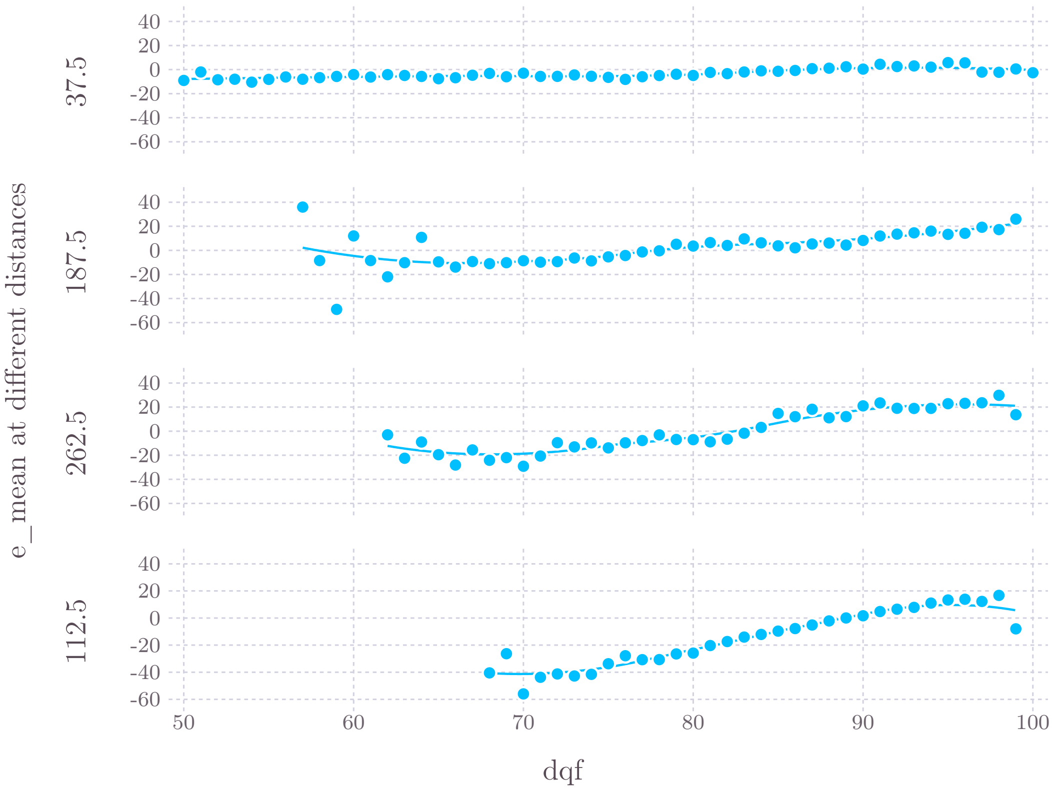

Figure 4.9: Mean Error (cm) by DQF across different distances (cm).

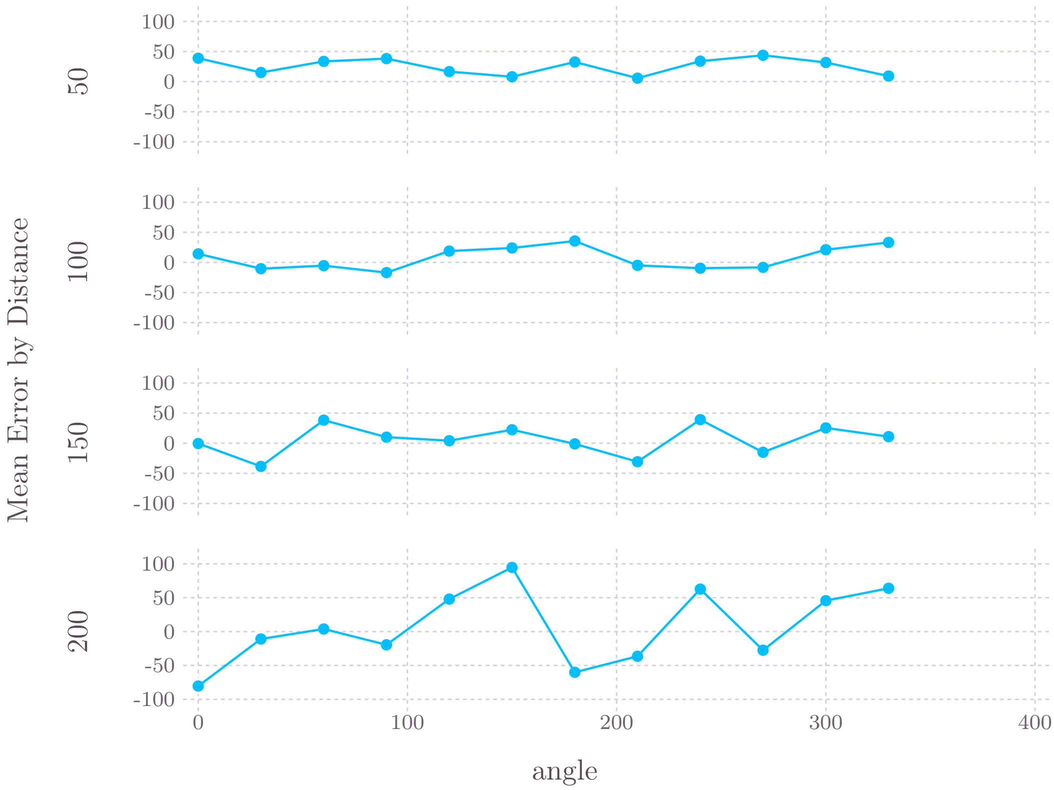

Figure 4.10: Mean Error (cm) for Given Angle

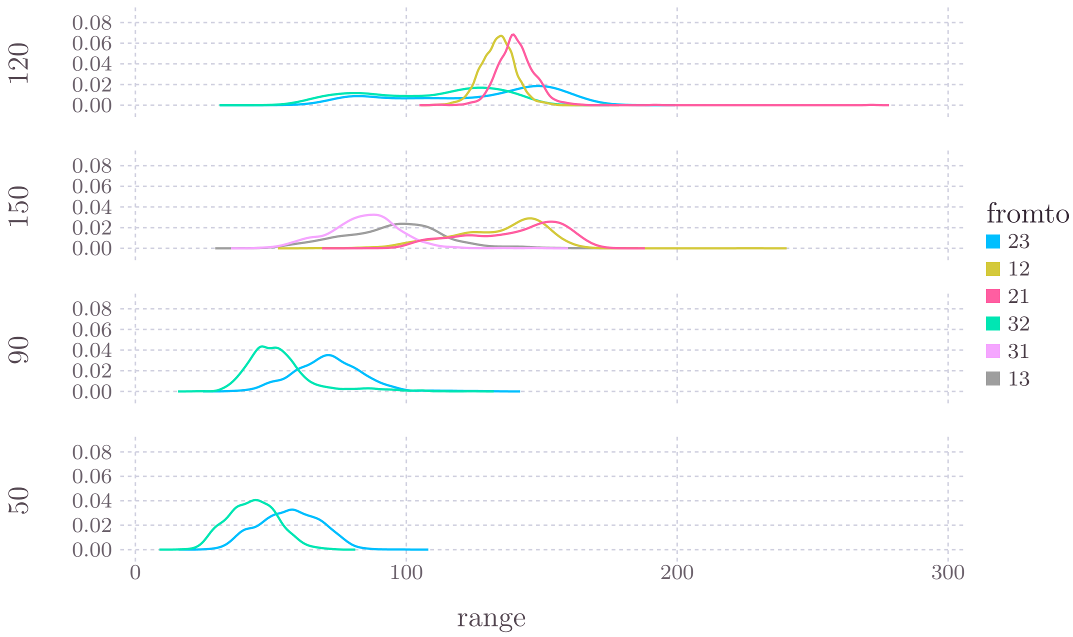

Figure 4.11: Symmetric Rangings. For each of the distances (cm) the density of the range (cm) has been plotted. The colour encodes from wich node to which node the ranging took place.

5 Future Work

In this chapter an outlook is given on what needs to be done to further integrate the ranging modules into the FINken robots and to improve the values yielded.

Additionally, possible applications for the ranging sensors have been gathered during the course of this work.

5.1 Next Steps

There are some improvements that can be immediately made on this work. Further evaluation might still yield interesting results and of course the sensor still needs to be integrated into the FINken.

5.1.1 Evaluation of RF-noise

With more equipment and expertise in high-frequency engineering a much more detailed analysis of RF-noise, antenna- and frequency selection could be done. The ranging quality will benefit from optimising on those parameters.

5.1.2 Influence of Movement

Since it was not possible to move the nodes in a predictable manner while still measuring a reference value in our lab, there is no data on the effect of movement on the ranging nodes. As the copters are capable of flying very fast their movement could alter the measurement quality, since multiple phase difference measurements are combined into one range value.

5.1.3 Further Integration

Albeit the range measurements are not great, the ranging sensors could still be an improvement to having no ranging capabilities at all. To achieve this one of the possible hardware solutions suggested in subsection 2.1.1 needs to be purchased and integrated into the FINken.

The final sensor should be evaluated again. Kempke, Pannuto and Dutta [14] show how inflight validation of range measurements is done for TOF localisation. A similar setup might be used to validate the ranging capabilities of the new FINken sensor.

5.1.4 Improve Range Values

Of course the range values could also be improved algorithmically. In this work no filtering of valid measurements was performed. However, the results will be improved by computing range values based on multiple measurements. It would beneficial be to find a "clever" way of filtering, that takes the distribution of the values into consideration. A better theoretical model for the distribution of the error would be needed to exploit implement such a filter.

An interesting way to implement such a filter is to use interval arithmetics. As there are big changes in the measured range values when small changes in the distance of the nodes occur the intersection of the intervals could provide good results.

5.2 General Applications for Quadcopters

The motivation to study the ranging sensors was to obtain a distance measure within the swarm of robots. Nevertheless, the robots could benefit from the new sensors in other ways.

5.2.1 Flying with Pseudo-GPS

Normally, the paparzzi autopilot is used outdoors. The FINken robots can only use a small subset of the autopilot's features, as many of those features rely on a GPS based position- and heading estimate.

A GPS device can be emulated using a ranging based position estimate. In order to use such an emulated GPS a multilateration algorithm has to be implemented for the ranging nodes. Furthermore, the position estimate needs to be integrated as new GPS module for paparazzi.

5.2.2 Virtual Walls

Currently, nets and ultrasound reflecting foil are used to enclose the flight area. Those could be replaced by ranging beacons, that enclose the operating area. This can be achieved either by computing a position and defining coordinates which should not be left or by placing ranging nodes in the area and defining a minimal distance to the nearest node. This could be a convenient setup for mobile deployment of the FINken robots.

5.3 Applications in Swarm Robotics

Finally, some concepts for range based swarm behaviour for the FINken robots will be suggested.

5.3.1 Direction

A value that the ranging sensors do not yield is the direction of the refletor node. For use in some swarm algorithms this is a problem: Acting based on virtual attraction and repulsion forces is a common approach in swarm intelligence. However, those forces are directed and information about the direction of the nodes cannot be gathered with the ranging sensors.

A sense of direction may still be gained, by using anchor nodes for orientation.

5.3.2 Distance Based Swarm Objectives

Swarm behaviour can be used for multi-objective optimisation. Those objectives can be based on the measured distance i. e. staying close to a specific node or staying away from a specific node. Keeping a minimal distance or maximising the distance between the robots might be used to avoid collisions between multiple robots. Avoiding collisions is an important requirement for the ermergence of a robotic swarm.

By maintaining fixed distances among each other the swarm could form stable formations.

5.3.3 Collision Avoidance

Similar to the bounding boxes from subsection 5.2.2 the distance sensors may be used to enhance collision avoidance in between the copters belonging to the swarm. This will especially be useful if the safety distance in between the robots is higher than the safety distance kept to neareby objects that are not part of the swarm. As the copters influence each other by creating turbulences, this strategy could provide benefits for the behaviour of the swarm in particular in small rooms.

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Declaration of Authorship

I hereby testify that I have written the whole of this thesis myself and without external help and used no sources or aids other than those named. All passages taken from a source, whether verbatim or in substance, have been indicated as such.

Sebastian Mai