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# Wireless Ranging in Swarm Robotics

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**FAKULTÄT FÜR  
INFORMATIK**

Institut für Wissens- und Sprachverarbeitung

Bachelor Thesis

## **Wireless Ranging in Swarm Robotics**

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This paper evaluates how suitable the Atmel RTB ranging sensor is to be used in the FINken robots.





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Caption



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# 1 Introduction

## 1.1 Motivation

The FINken project aims to create 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 distance in between the robot.](#)

source

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 shall be able to measure the distance to another sensor based queried by address.

## 1.2 Requirements

There are basically three requirements for the ranging sensor. Those requirements will act as a base to choose and to evaluate the new sensor.

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

### 1.2.1 Interaction between Copter and Ranging

The copter shall not influence the function of the ranging modules and vice versa. I.e. 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 to a point where the sensor values of both sensors are completely useless.

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

wording

### 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 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 shall interact locally to form a swarm in contrast to multi agent systems that rely on global information. As a consequence measuring the positions of the copters with an external sensors and providing the distances via telemetry is not sufficient—the robots shall not be dependant on external 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 by 4 m so the range measurements need to be pretty accurate for small distances. Additionally the update frequency needs to be quite high as the copters are able to move with great accelerations and velocities.

provide metric for hypothesis

moar!

## 1.3 The FINken Robot Platform

Goal of the FINken project is to implement intelligent swarm behaviour on flying robots and research how swarm collaboration works in a real world

application. The robots need to fly in an stable manner on their own and be capable of interacting without disrupting the operation of the other swarm members. Those robots shall 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 directly attached to a brushless motor. In combination the motors can be controlled to change the direction of the thrustvector (pitch and roll), to change the overall amount of lift generated (thrust) and to change the orientation of the airframe (yaw). The airframe houses all the actuators, processors and batteries needed for flight. Additionally it carries a multitude of sensors used for operating autonomously.

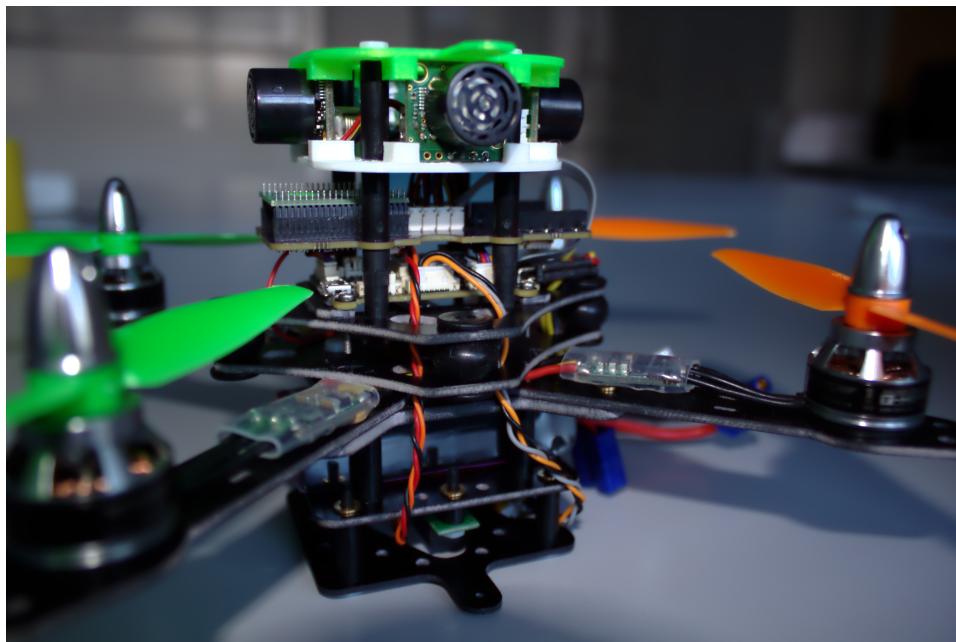


Figure 1.1: The FINken robot, revision 3

The robots are capable of highly dynamic flight maneuvers—the robots have enough acceleration to leave the operating environment in any possible direction in under one second. This is mainly because the robots need lots of payload capacity to carry different sensors and computing power, with enough

headroom to make changes in the future. However the capability for dynamic behaviour is not useful for our research. Of course the high power of the motors can also be used to stabilize the copter better, which is exactly what is needed for the FINken research. If the copter is angled by only  $6^\circ$  and its height is kept stable it is accelerating at about  $1 \text{ m s}^{-2}$  if the height stays the same during that time. This means the copter reaches a velocity of over  $2 \text{ m s}^{-1}$  when travelling through the arena at this pretty small angle.

kleine  
störung->  
rel. großer  
effekt

### 1.3.2 Environment

When doing research things do not always work perfectly. Therefore the environment for the FINken robots is designed to protect the robots from mechanical damage. It is also designed not to interfere with 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 without damaging the robots if they fail to elude them. Usually the altitude of operation is between 0.5 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. It is possible to create virtual environmental factors by using a projector and an rgb-sensor mounted on top of the robots. This virtual environment can be used to research the behaviour of the quadcopters if a certain task is assigned to the robot, e.g. finding the brightest spot.

### 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.

#### Autonomous Flying

To form a swarm the robots need to function as single individuals first—that means not crashing into walls, ceiling, floor or other robots. Of course the sen-

sors needed for autonoms flight must not be disturbed by the other componets of the quadcopter.

To simplify the control of the quadcopters no complex movements shall be made. The robots shall be able to fly at a given height and navigate in x-y-direction to perform their given tasks. Flying autonomously like this requires to solve two major problems: Height control and navigation.

For controlling the height of the copters either the ultrasound distance measurement of the optical flow sensors are used, alternativly the height is measured by an infrared sensor that needs to be equipped when the optical flow sensors are not.

Navigating the x-y-plane is a much harder task. Because sensors are not perfect the copter will drift in any given direction and precise speed and position measurements are lacking with the current sensor setup. As a consequence implementing a position hold or navigation by waypoints is not possible. Even without those navigation methods there is a well working strategie for flying for longer time periods. With its ultrasound distance sensors the robot can sense its surroundings and is able to stay in the arena by maintaining a safe distance from the walls of the arena and other objects in the way. An essential precondition for navigating around obstacles that way is avoiding highly dynamic maneuvers.

link to  
christophs  
ba

## Interaction

The FINken robots shall be able to do more than randomly flying around without crashing. The robot shall interact with its environment and it's neighbours in the swarm. Of course sensor values needed for autonomous flight can also be used to interact with the robots environment, but there are also senors that are exclusively used for interaction.

To interact with it's environment the robot has different sensors. The ultrasound distance sensors are used to measure distances to near objects. However those sensors are not able to distinguish between those objects and are in this respect very different from the new ranging sensors. To research interaction with an environment a solution is necessary to create a modifiable environmental factors that can be acted upon by the robots. Those environmental factors shall be changed without altering the physical layout of the lab. In the

swarmlab a beamer is used to project an into the operating area. The current lighting situation can be measured by an rgb color sensor that is mounted on top of the copter.

The new range sensor is also mainly used for interaction between the robots. It can be used to create environmental input for example to provide points of interest or to mark certain locations that shall be avoided by other quadcopters. Ranging values enable the FINken robots to interact with each other based on their distance i.e. by implementing attraction-repulsion-behaviour.

more?

### 1.3.4 Hardware Description

There are different ranging technologies that might be used in a FINken quadcopter. However there are different components that can interfere with the new sensor that shall be integrated e.g. by disturbing the measurements made by the new sensor.

Part	Description
Frame	The Frame is made of GFK material and plastic and rotor to rotor distance is 10 cm
Propellers	The FINken use 5" x 3" 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 distances of 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, alternative to optical flow sensor
Telemetry	BTLE-/Zigbee modules to exchange data with the ground station
RC-Control	2.4GHz based Radio Control to manually control the robots

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.

It is still interesting to search for positioning applications, since many of those positioning technologies are based on multilateration<sup>1</sup>. [5]

keep it or  
throw it  
away?

### 1.4.1 Optical Tracking

Most projects use external optical tracking to measure the position and orientation of the quadcopters.

refs

The most common optical tracking systems are very costly in comparison to the other ranging methods described here. The most affordable solution from Optitrack that is able to track 5 targets at once costs more than 10 000 \$[21]. The price is justified by the superior performance of this method. This means tracking accuracy as well as the possibility to measure orientation at a very high update frequency.

research  
performance  
statistics  
for ranging  
solutions

ETH

However this approach is exactly the multi agent systems approach to provide global knowledge that has been gathered by the tracking system to the agents in contrast to swarm behaviour that is relying on local information. The biggest drawback of this approach is that we gather global knowledge about our system, rather than creating behaviour based on local interaction. As such external tracking would be a valuable tool for evaluation, but is not meeting the requirements for gathering sensor data.

---

<sup>1</sup>The usual methods for positioning are: *multilateral*—which is what we are interested in because only ranging measurements are used, *multiangular*—which is no use to us, because angle measurements are used and by *orientating in a map* with different factors like beacon-positions—which is also no use to us.

### 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 [18] state, that standard errors of  $2.6 \text{ m}_{\text{RMS}}$  and  $1.8 \text{ m}_{\text{RMS}}$  was measured in different indoor scenarios. With an operating area only 3 m wide this approach is not suited for our robots.

A project that looks more promising is decaWave. According to [17] the measurement error is generally under 1 m and with filtering can be brought to below 15 cm. The proposed method of filtering needs 27 measurements to compute one range value. However the decaWave project was unknown to us when we started looking for ranging possibilities so

wording

blabla

### 1.4.3 Ultrasonic Time of Flight Ranging

A very clever approach to ranging is used by ranging solutions like cricket [24] and active bat [28]. 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. In fact the time periods get so long that another problem comes up.

Using sound as medium there is an upper bound to the update frequency for all nodes sharing the medium (i.e. close enough to sense each other). [28] claims that one ranging measurement can be done in a 20 ms slot. That means we can have 50 range updates per second. Assuming we have a swarm of five robots that form a fully connected graph we would need at least ten range measurements to get all swarm distances. So the upper boundary for ranging update frequency in a swarm of five robots is 5 Hz. Considering that this is the upper limit this is a solid disadvantage of this method. Furthermore the FINken robots currently use sonar based distance sensor to measure the distance to the nearest object in some direction so either the update frequency would be diminished much further.

In conclusion ultrasound based ranging is a very neat approach to ranging that is already used in other quadcopter projects [12]. 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<sup>2</sup>-based ranging is done for several different wireless technologies: Bluetooth[22], WLAN[16, 19], RFID[13].

The main factor that rules out RSSI-based ranging is that radio-waves are not propagated equally in every direction. As a consequence the orientation of the antenna might have a much bigger impact on signal strength than the distance. Additionally radio waves might be weakened when travelling through the FINken robots.

typical propagation pattern picture

#### 1.4.5 Atmel RTB, Dresden Elektronik, Meterionic

Another thing that can be measured phase shift. This is a principle that is used by some of the ultrasonic methods. However the phase difference can also be measured in radio waves. This is utilized by the ranging hardware from the Atmel Ranging Toolbox. Multiple frequencies are used to measure a phase difference. Because the wave length changes with different frequencies you can take all of the measured phase differences and compute a distance. Similar hardware using the same software stack is also sold by *Dresden Elektronik* and *Meterionic*.

quelle

Using phase differences in RF discards 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.

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<sup>2</sup>Received Signal Strength Indicator



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## 2 Integration Concept

As stated in section 1.2 the sensors shall be integrated into the FINken robot in a way that 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 too 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.

wording

### 2.1 Hardware

#### 2.1.1 Ranging Hardware

There are several different possible hardware platforms for the Atmel ranging software. At the time this thesis started using the firmware of the Atmel Ranging Toolbox [7] for the REB233SMAD Evaluation Kit [8] was the only setup that was already supporting ranging.

For evaluation those modules are quite useable, 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 802.15.4 modules from dresden elektronik which are already integrated into the new hardware revision of the FINken robots as telemetric transmitter. Another way to integrate this approach to ranging into the FINken robots is to miniaturize the REB233SMAD-modules, by leaving unused PCB-area and connectors.

other frequency

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

### **2.1.2 Assembly**

As it is unclear which version of the ranging hardware is best 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 header currently used for the telemerie 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 quatcopter 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 Autopilot Software**

The FINken robots are controlled by a micro controller handling all the computation needed. There is no distinction between higher level logic like path-planning and low level code as the stabilization of the copter in terms of hardware. The exact board that is used is the LISA/MX autopilot board in hardware revision 2.1 [1] 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 possible interfaces.

An important design decision is how to devide 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 it also means that there is no convenient way of getting 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 free up 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 only the raw values of the sensors are used. However it might still be a good idea 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 similar across 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

There are some different methods of connecting the new sensor to the paparazzi autopilot. All of the following ways of connecting hardware are supported by the LISA/MX board and one has to be chosen for the new ranging sensors.

### 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 need 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 we do not only need to read a range value from the sensor but we also need to tell the sensor which value to fetch. Therefore some kind of bidirectional communication between autopilot and sensor need to take place. The big advantage of using a GPIO pin would be that only one single wire<sup>1</sup> 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. [27]

The disadvantage of the UART protocol is that it is a strictly bidirectional 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 used.

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<sup>1</sup>Two additional wires are needed to supply the sensor with power, those wires will be needed regardless of the communication protocol.

not clocked  
-> slow?

Using the last of those ports is not feasible as there are other better options available.

### 2.3.3 SPI

Serial Peripheral Interface is a four wired bus that also allows bidirectional communications. There are two modes of operation that can be used in SPI. In the independent 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 bandwidth. This means the sensor would need to be capable of high clock speeds and data rates in order to keep the bandwidth for the other applications up.

wording  
fact-check

### 2.3.4 CAN bus

wording  
more, fact-check

Controller Area Network is a bus protocol mainly known for its applications in the automotive area. 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.

### 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 already are multiple sensors connected to the autopilot via I2C. All of the ultrasound-sensors and also the optional color sensor use I2C to communicate with the autopilot. This also means that there is already know how and code that can be utilized 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 independent 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 sensor network on the FINken makes I2C the best choice as a communication protocol for the new sensor.



---

# 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 Communication Interface

### 3.1.1 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 data answering the request. The registers are listed in Table 3.1. In normal operation the master device will set reflector and initiator address, initiate the ranging and read 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. The I2C-address is the address of the I2C-device, that needs to be changed to avoid address collisions i.e. when multiple ranging nodes are used with one master device. The short address is the address describing the ranging node. 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 addresses on multiple devices.

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

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.

Initiator and reflector address refer to the short addresses of the nodes on both ends of one measurement. The initiator is the ranging node starting the ranging process, the reflector its target. Because 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.

### 3.1.2 Datafields in the Ranging Result

Table 3.2 describes how the structure for transmitting range values is organized. The reason why so many values are included into the range measurement is that the master device is most probably needs to do filtering based on status and dqc-values. The addresses of the nodes are included to match measurements in case one of the packets is lost or a new measurement is made before the old value is read.

The data type for the range values is changed, not to block the I2C-device unnecessarily the data type of the range reading is changed. Instead of the

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

original 32-Bit value only a 16-Bit value is used, as distances up to more than 60 m are more than plenty in our application.

## 3.2 Python Scripts

For testing the sensor nodes and also for aquiering the data for evaluating the sensors I set up a RapsberryPi minicomputer as I2C master. Using this setup for testing has proven really usefull. Gathering data with those scripts might be a suitable way to develop and test software using higher level concepts, without the need to write code for embedded devices.

*i2cranging.py* contains functions for the master side of I2C communication. Those can either be used from the python PEPL or by other scripts. *poll\_range.py* contains a convenient method to take continous range readings from the unix shell and is mainly used to generate csv-files with ranging values. Those csv-files have been used for evaluating the ranging nodes.



---

# 4 Evaluation

The fullfill the first two of the 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<sup>1</sup>.

ranging  
modules

The evaluation of the sensors is made difficult by the fact, that there are many interdependent variables that influence each other in unclear ways. The ranging method itself can only be treated as a black box up to the ranging api provided by the Atmel RTB firmware. Especially the effects of RF-noise and multipath propagation are environmental influences that are not controllable and hard to measure but still have great influence on ranging quality.

## 4.1 Robustness of Implementation

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

With the current hardware this integration can not be done completely, because the current hardware plattform is simply to big to fly. This step of integration will be done with the .

de-modules

### 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 a malfunctioning sensor might render the others sensors useless, in worst case crashing the copter.

At the moment the ranging sensors cause bus hangups, when rangings are requested to often.

measure

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<sup>1</sup>see subsection 1.2.3

### 4.1.2 i2c errors per time

Another problem that may occur is that i2c data packets can get lost. This would mean the autopilot has to rely on expired data and it might break any kind of derivative computed from the range value. .

jaja, als ob  
man da was  
sinnvolles  
ausrechnen  
könnnte :(

measure

## 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, because there are lots of interdependent variables that influence ranging accuracy.

### 4.2.1 Frequency Selection

move to im-  
plementa-  
tion?

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

Comparing the utilization 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 things can be noticed. The noise in the frequency range for ranging is much lower than on frequencies 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). You can already see that the peak can still be lost in noise like it is shown in the FFT plot but is very stable over time as you can see in the waterfall plot.

Because of the lower utilization 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. These 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 that impact ranging quality that can not be measured that easily – at least the quality of the antennas for different frequencies and the impact of the number of available channels in the frequency range and channel spacing are variables that can not be directly measured in our lab<sup>2</sup>. In the end this means finding the right parameters for ranging frequency settings is a really hard problem, especially because measuring the ranging error over many frequencies takes lots of labtime. It is not viable to measure all available combinations for those parameters.

Find out antenna measurements / calibrated antennas

wording

labtime + lab utilization ... ?  
or is this to mimimi

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<sup>2</sup>The sourcecode and algorithms used by the modules is closed source, so we are not able to infer the effect of channel spacing and number of channels from that.

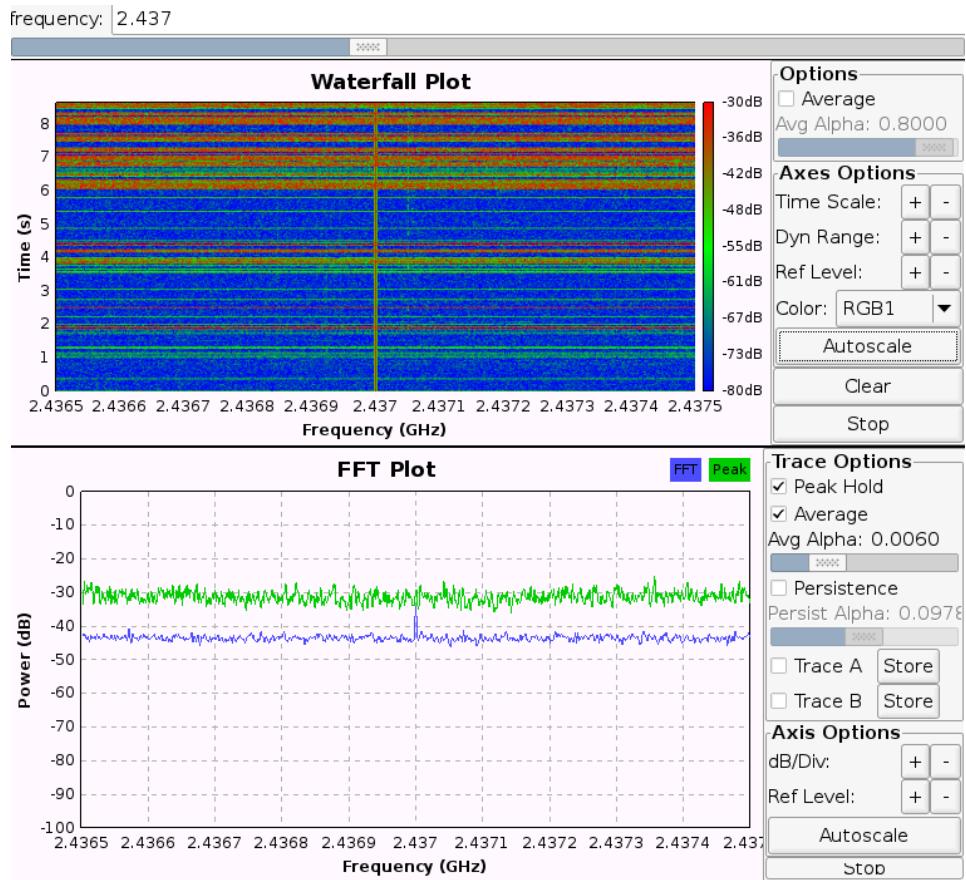


Figure 4.1: RF-Spectrum on 2.437 GHz

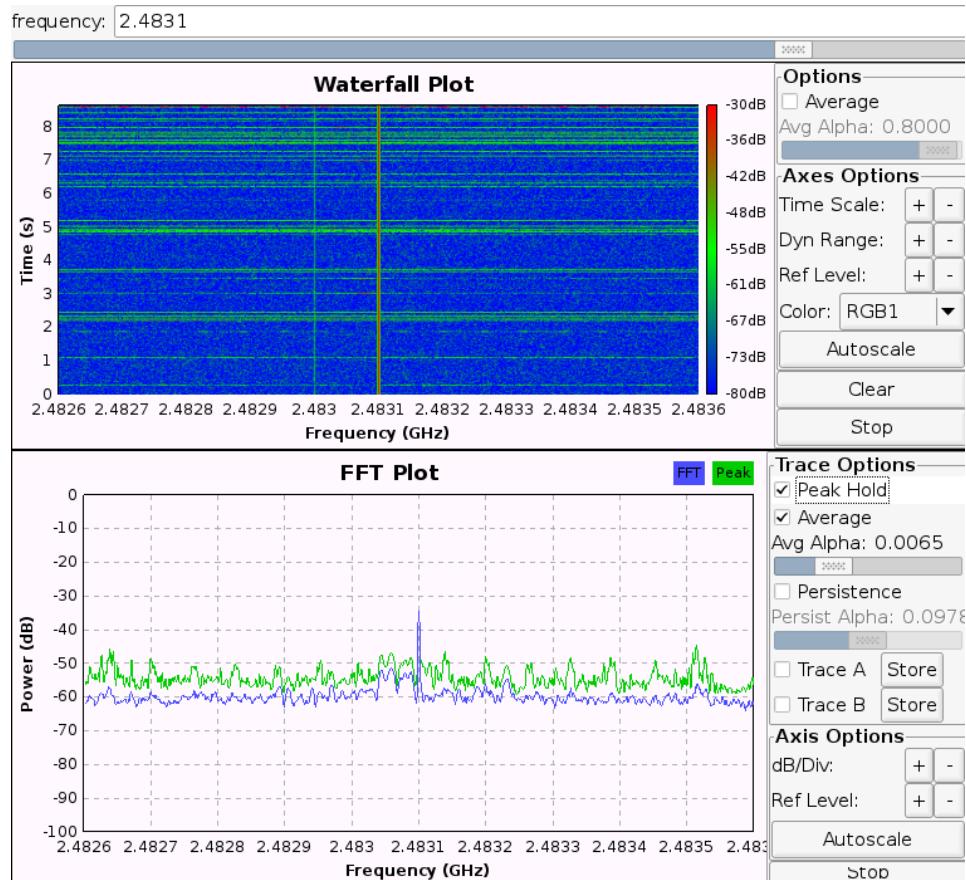


Figure 4.2: RF-Spectrum on 2.483 GHz

Even with those frequencies the measurement is only really working when the lab is empty, as basically every person in the lab uses several devices that use the 2.4 GHz frequency range. To create a usefull evaluation all the following measurements have been made with an empty lab out of the working hours of the people in the buliding. However this problem must be addressed before the sensors can be used in a real world application. This is especially true because the remote control is causing the worst interference with the ranging nodes observed so far.

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 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 minimize 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 amount of RF interference by 2.4 GHz devices can be expected

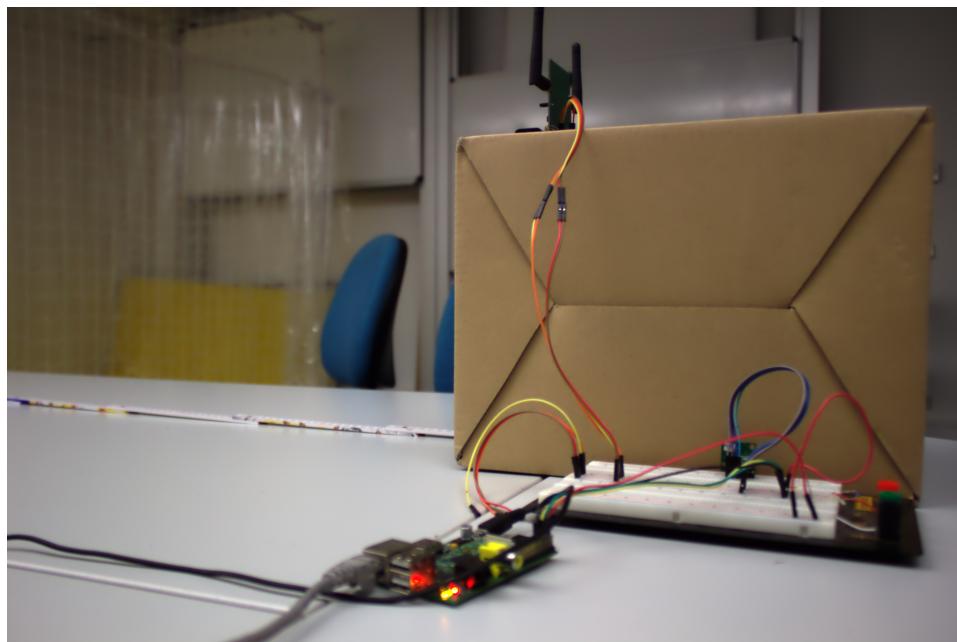


Figure 4.3: Measurement Setup

### 4.2.3 Influence of DQF on Range Values

One value the ranging api provides is the DQF<sup>3</sup>-value. It is reasonable to expect a huge amount of scatter for lower DQF values. As Figure 4.4 shows this is not how the range value behaves.

For the values measured with 1m real distance we can see that the values measured with lower quality do not have the same mean value as those with higher quality. Also values measured with lower quality are closer to each other than those with higher signal quality. As long as we only look at the values taken at 1m real distance it seems like we could be able to improve the range estimate by including the dqc value into the computation of the distance. To do that this behaviour would need to be stable across different distances, i.e. no matter if the measurement is taken at 1m or 3m distance the when the dqc is low the measured range is lower and if dqc is high the measured range is higher.

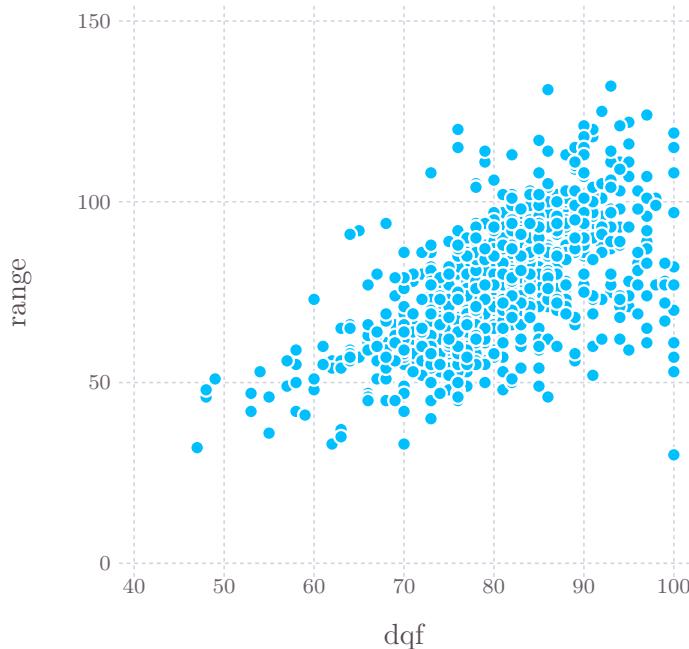


Figure 4.4: 1000 values measured at 1 m distance

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<sup>3</sup>Data Quality Factor

Figure 4.5 shows measurements taken at different distances. The values for further distances have far more noise than values for lower distances. This leads to bad consequences.

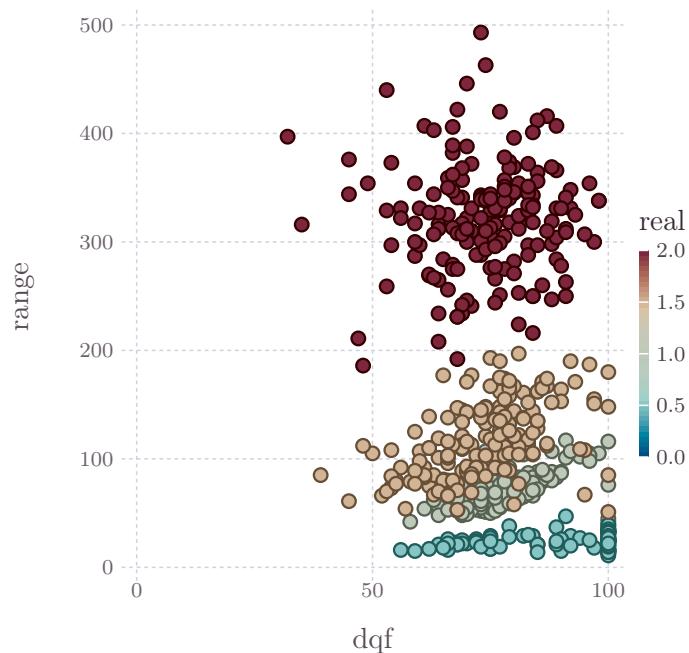


Figure 4.5: values measured at 0.5 m to 2 m real distance

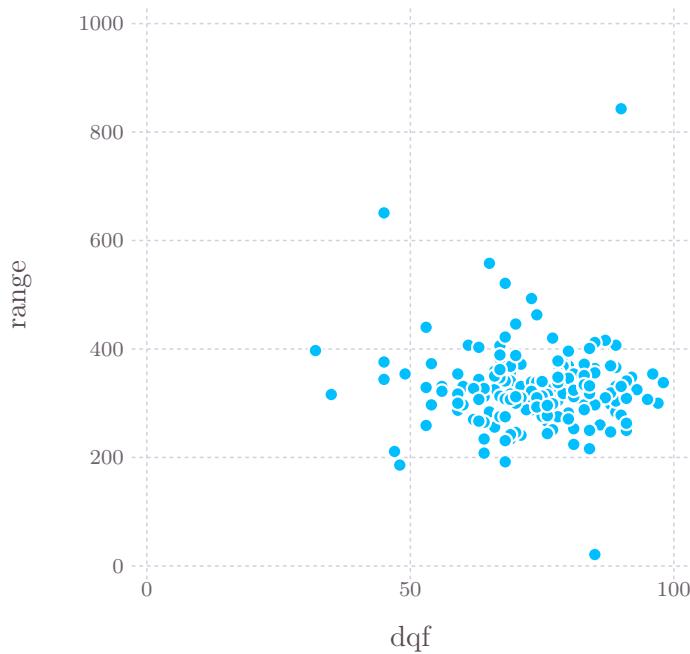


Figure 4.6: 100 values measured at 2 m distance

#### 4.2.4 Influence of Distance

It is important to know how the ranging nodes behave at different distances. In Figure 4.7 this relationship is shown. The results are not what was hoped for when the hardware was selected. As you can see in Figure 4.7 the lower values yielded for any given distance might be in the interval yielded for pretty much all distances. Additionally the mean values are not even nearly monotone, there are some irregularities in the values where a higher distance leads to lower range values.

prettify

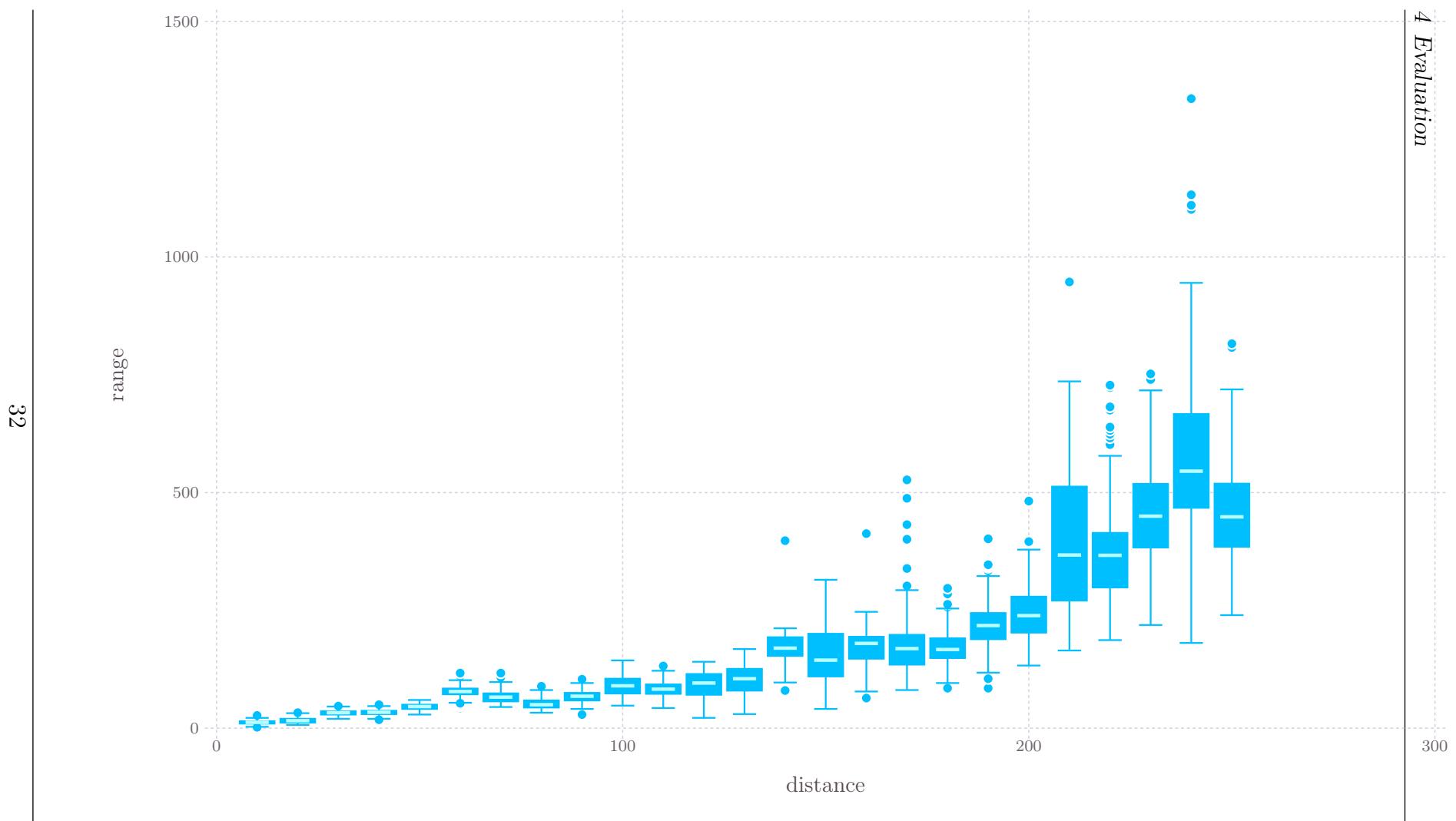


Figure 4.7: range values and real distance

## 4.2 Ranging Accuracy

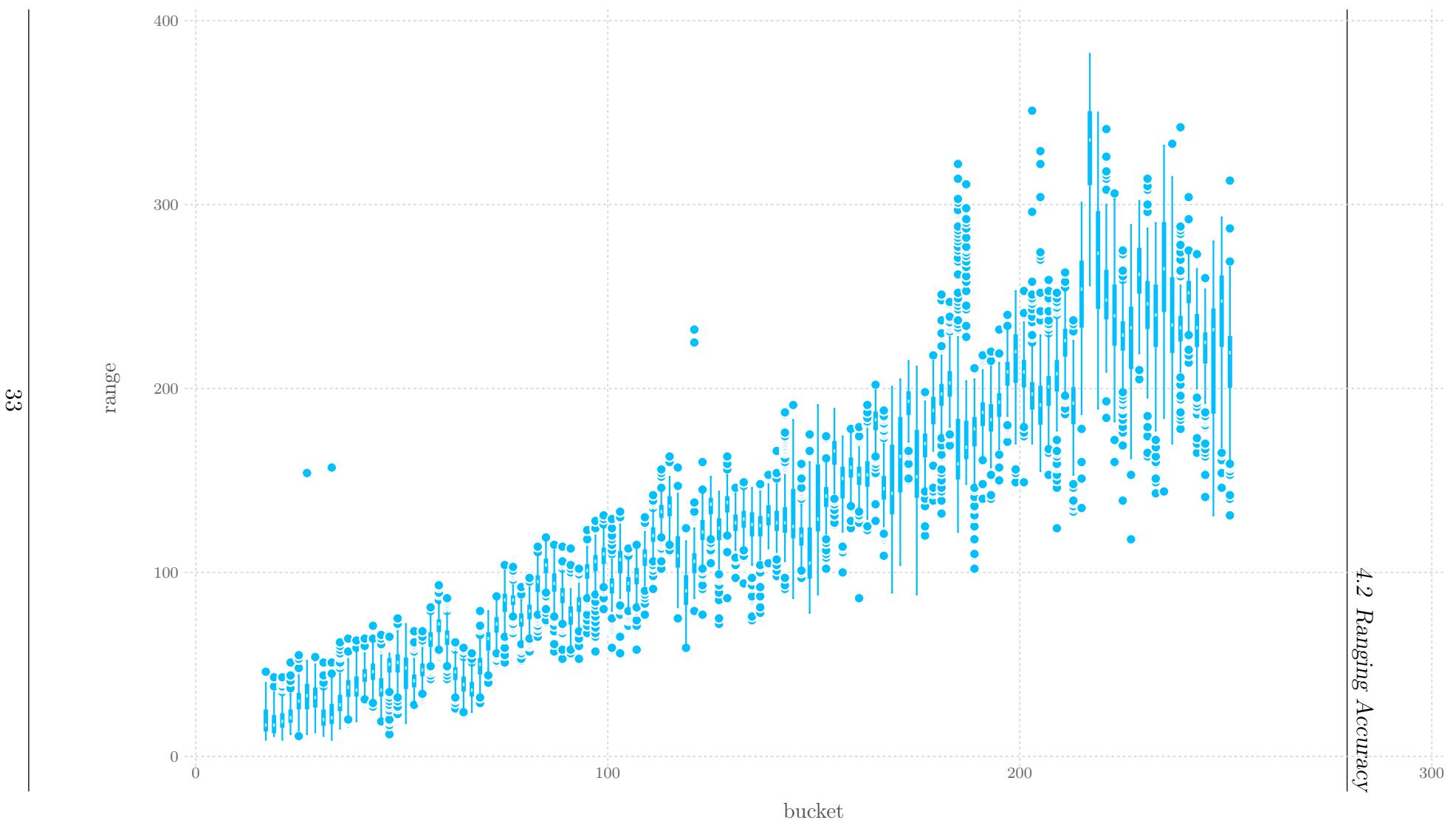


Figure 4.8: Range values with 2 cm resolution

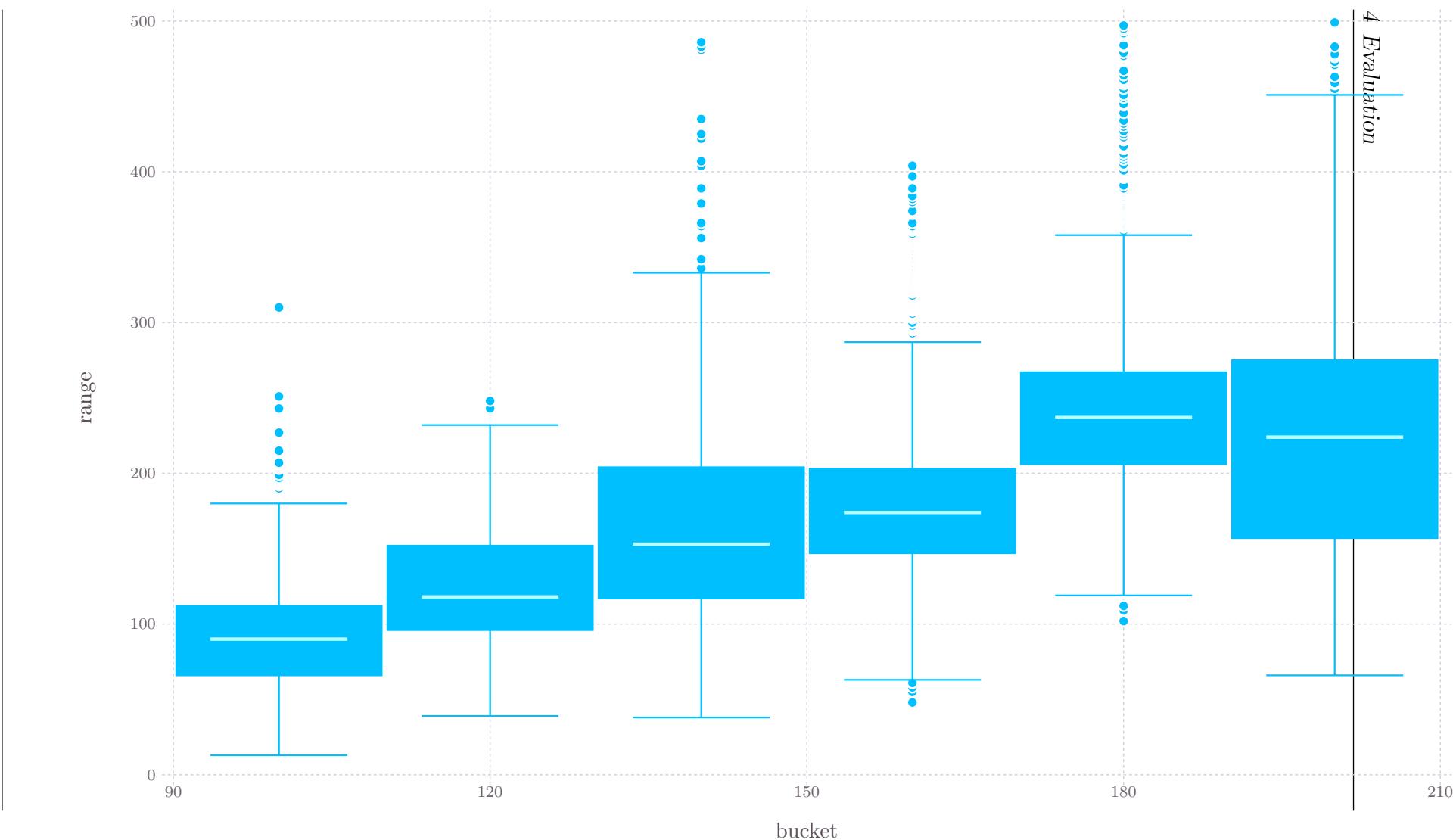


Figure 4.9: Range values with 1 cm resolution each bar represents all the values in the range, with bucket size of 20 cm

Looking at a smaller resolution of distance values you can see exactly the same thing. This seems very bad at first glance. However the values look much better when multiple readings are combined. The result of this approach is shown in Figure 4.9.

However we can not simply measure 20 values to compute a filtered value at once, especially as the values must not be measured at the same distance. As long as the quadcopter is moving measurements could be taken continuously.

caption for  
buckets  
(wording)

#### 4.2.5 Antenna Orientation

(diversity,  
no diversity)  
\* (parallel,  
perpendicu-  
lar)

#### 4.2.6 Orientation of Devices

#### 4.2.7 Moving Nodes

Movement has an influence on the quality of the range values depending on the ranging method used. For the phase different measurements a moving node could mess up the range value if the phase differences measured at multiple frequencies don't match the same distance because the node moved in between.

wording

However moving the node in a defined way and taking a measurement at a fixed distance is a sophisticated task.

#### 4.2.8 Ranging on FINken Robots

### 4.3 Properties of a Distance Function

The ranging sensor on the FINken robot shall be used to provide a distance between two quadcopters, similar to a distance measure used in swarm intelligence algorithms. In the pure mathematical sense a distance function has to fulfill certain properties.

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

$$f(x, y) \geq 0 \quad (4.1)$$

$$f(x, y) = 0 \iff x = y \quad (4.2)$$

$$f(x, y) = f(y, x) \quad (4.3)$$

$$f(x, z) \leq f(x, y) + f(y, z) \quad (4.4)$$

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 break the pattern 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 clearly positiv. Also the property of coincidence is always given. Each module has a unique address and is therefore able to check, if it is ranging itself. Having two modules occupy the same physical spot is obviosly 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:  $A \rightarrow B$  means a range reading is taken from node A with B as reflector node.

Symmetry is a property that can not be achieved by the ranging sensors because of noise. A range reading  $A \rightarrow B$  will not be equal to the reading for  $B \rightarrow A$  just because the two readings will be altered by noise. The question that remains is: Do we have the same error for both directions.

plot, evaluate, spoiler alert: Nope!

However the lack of symmetry might be utilized.

$$\frac{d(A \rightarrow B) + d(B \rightarrow A)}{2} \quad (4.5)$$

data

The remote ranging ability of the nodes can be exploited to gather both values  $A \rightarrow B$  and  $B \rightarrow A$  by averaging those values the error might be lowered. The new value shown in Equation 4.5 will be symmetric. The measurement error will be reduced because of the averaging.

### 4.3.3 Triangle Inequality

The triangle inequality will also be broken by noise. I.e. if we measure  $d(A, B) + X + d(B, C) + X$  and  $d(A, C) + X$  the measurement error  $X$  might as well break the condition of the Triangle Inequality.

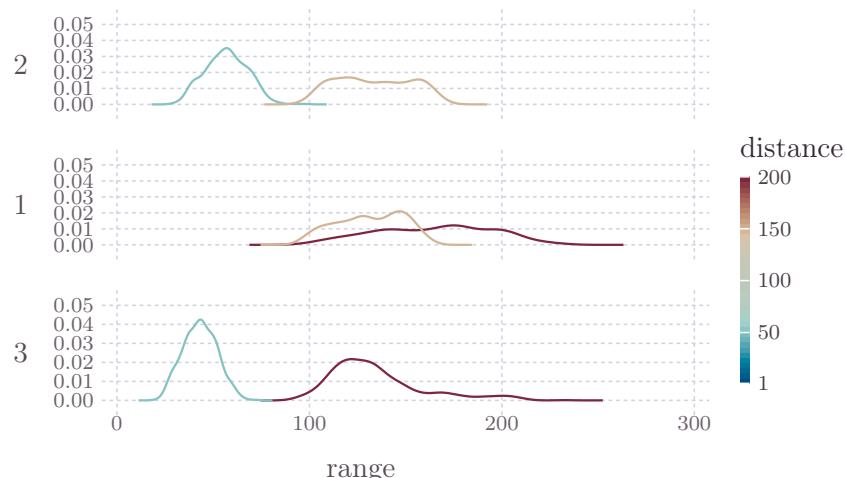


Figure 4.10: Density functions for 3 nodes, Nodes were placed in a straight line with numbers 1, 2, 3. Distance 1-2 was 150 cm, distance 2-3 was 50 cm.

## 4.4 Conclusion

Let's take a look at the requirements from section 1.2. It is possible to integrate the sensor nodes into the FINken robots, however not in the current hardware setup. The interference of copters and sensors is not as easy as was thought. RF-Interference disturbs the function of our distance sensor. At least the functionality of the copters does not seem to be disrupted by the ranging

-> unpersonal lingo

nodes. It is still possible to solve this problem by changing the hardware on the copter or the frequency the ranging nodes operate at.

wording?

In the end the quality of the range measurements is deciding if the requirements are met. The measured range values are not as good as was hoped for. A filter needs to be implemented to compute a usable range estimate should be given. This would introduce a time delay into the measurement which is not desireable.

wording

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

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# 5 Future Work

## 5.1 Improving the Ranging Sensor

### 5.1.1 Influence of Movement

Improving  
vs. Influ-  
ence of  
Movement

Since it was not possible to move the nodes in a predictable way 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 the fact that they are moving could alter the measurement quality, since multiple phase-difference measurements are combined into one range value.

### 5.1.2 Further Integration

Albeit the range measurements are not great the ranging sensors might still be an improvement to having no ranging capabilities at all. To achieve this one of the possible hardware solutions from ?? needs to be purchased and integrated into the FINken. The final sensor should be evaluated again. Lanzisera, Lin and Pister [18] 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.

### 5.1.3 Improve Range Values

Of course the range values can also be improved mathematically. In this work no filtering of valid measurements was performed. However the results might be improved by computing range values based on multiple measurements. A

good way of doing this would be to find a “clever” way of filtering, that takes into consideration the distribution of the values. To exploit the distribution of the values a better theoretical model for this distribution would be needed.

formulieren  
als vorschlag

One way to filter the values like this is by using interval arithmetic. As there are big changes in the measured range values when small changes in the distance of the nodes occur the intersection of the interval might provide a good measure.

filtering ->  
papers

## 5.2 General Applications for Quadcopters

### 5.2.1 Flying with Pseudo-GPS

One of the things that can be done with ranging is position estimation via multilateration. Even if the FINken project is mainly interested in gaining a viable distance measure between individuals in a swarm a position estimate would be beneficial for the performance of the autopilot-especially as the normal use case for the Paparazzi autopilot is outdoors and with a GPS receiver attached.

To integrate positional data into the FINken two steps are needed: Implementing the multilateration algorithm on the sensors and writing a new GPS module that uses the data from the sensor. An additional benefit of using anchor nodes to compute a position estimate is that we can find out our current heading and the direction of other swarm entities much easier

### 5.2.2 Distance Based Fencing

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, either by computing a position and defining coordinates which should not be left or by placing ranging nodes in the area and defining a minimum distance to the nearest node. This could be a nice setup for mobile deployment of the FINken robots.

## 5.3 Applications in Swarm Robotics

### 5.3.1 Direction

A value that the ranging sensors don't yield is the direction of the other sensor it is ranging with. For use in swarm algorithms this is a problem: Normally we compute a force towards or from the other swarm entities that is based on distance and direction. This way is still blocked for us as we can't measure direction.

### 5.3.2 Distance Based Swarm Objectives

Swarm behavior can be used for multi objective optimization. One of those objectives might be based on the measured distance i.e. stay close to a specific node or stay away from a specific node. Keeping a minimal distance and maximizing the distance between the robots might be used to avoid collisions between multiple robots. Avoiding collisions of course is one of the most important requirement for emergence of swarm behavior in a robotic swarm.

### 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 might especially usefull if the safty distance in between the robots shall be higher then the safty distance kept to nearyby objects that are not part of the swarm. As the copters influence each other by creating a lot of turbulence this strategy might provide benefits for the behavior of the swarm in small environments.

### 5.3.4 Formation Flying

One of the next steps is to algorithms from swarm intelligence to the FINken robots. The robots should be able to form a stable formation by using virtual attraction and repulsion forces to hold a given distance to their neighbors. If those distances are stable enough formations like triangle meshes can be formed.

get simulation data  
übertragen



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# Bibliography

- [1] *Lisa/MX V2.1 Autopilot.* [http://1bitsquared.com/products/lisa-mx-autopilot.](http://1bitsquared.com/products/lisa-mx-autopilot) – as seen at 2015-09-16
- [2] *Lisa/MX V2.1 Autopilot.* <http://1bitsquared.com/products/lisa-mx-autopilot>
- [3] *PaparazziUAV.* [http://wiki.paparazziuav.org/wiki/Main\\_Page](http://wiki.paparazziuav.org/wiki/Main_Page). – as seen at 2015-09-16
- [4] *PaparazziUAV.* [http://wiki.paparazziuav.org/wiki/Main\\_Page](http://wiki.paparazziuav.org/wiki/Main_Page)
- [5] *Multilateration.* <https://en.wikipedia.org/w/index.php?title=Multilateration&oldid=670629691>. Version: Juli 2015. – Page Version ID: 670629691
- [6] ALSINDI, N.A. ; ALAVI, B. ; PAHLAVAN, K.: Measurement and Modeling of Ultrawideband TOA-Based Ranging in Indoor Multipath Environments. In: *IEEE Transactions on Vehicular Technology* 58 (2009), März, Nr. 3, 1046–1058. <http://dx.doi.org/10.1109/TVT.2008.926071>. – DOI 10.1109/TVT.2008.926071. – ISSN 0018–9545, 1939–9359
- [7] ATMEL: *Atmel AVR2151: RTB Evaluation Application – Quick Start Guide.* [http://www.atmel.com/Images/Atmel-8442-RTB-Evaluation-Application-Quick-Start-Guide\\_Application-Note\\_AVR2151.pdf](http://www.atmel.com/Images/Atmel-8442-RTB-Evaluation-Application-Quick-Start-Guide_Application-Note_AVR2151.pdf). – online @ 2015-12-11
- [8] ATMEL: *Atmel AVR2160: REB233SMAD Evaluation Kit - Quick Start Guide.* <http://www.atmel.com/Images/doc42000.pdf>. – online @ 2015-12-11
- [9] BORENSTEIN, Johann ; EVERETT, Hobart R. ; FENG, Liqiang ; WEHE, David: Mobile robot positioning-sensors and techniques / DTIC Document. Version: 1997. <http://oai.dtic.mil/oai/oai?verb=getRecord&>

- metadataPrefix=html&identifier=ADA422844. 1997. – Forschungsbericht
- [10] BRISTEAU, Pierre-Jean ; CALLOU, François ; VISSIERE, David ; PETIT, Nicolas ; OTHERS: The navigation and control technology inside the ar. drone micro uav. In: *18th IFAC world congress* Bd. 18, 2011, 1477–1484
  - [11] CENTER FOR HISTORY AND NEW MEDIA: *Zotero Quick Start Guide*. [http://zotero.org/support/quick\\_start\\_guide](http://zotero.org/support/quick_start_guide)
  - [12] ECKERT, Juergen ; DRESSLER, Falko ; GERMAN, Reinhard: Real-time indoor localization support for four-rotor flying robots using sensor nodes. In: *Robotic and Sensors Environments, 2009. ROSE 2009. IEEE International Workshop on* IEEE, 2009, S. 23–28
  - [13] FU, Qing ; RETSCHER, Guenther: Active RFID Trilateration and Location Fingerprinting Based on RSSI for Pedestrian Navigation. In: *Journal of Navigation* 62 (2009), mar, Nr. 02, 323. <http://dx.doi.org/10.1017/s0373463308005195>. – DOI 10.1017/s0373463308005195
  - [14] GRZONKA, Slawomir ; GRISETTI, Giorgio ; BURGARD, Wolfram: Towards a navigation system for autonomous indoor flying. In: *Robotics and Automation, 2009. ICRA '09. IEEE International Conference on*, IEEE, 2009, 2878–2883
  - [15] HAZAS, Mike ; HOPPER, Andy: Broadband ultrasonic location systems for improved indoor positioning. In: *Mobile Computing, IEEE Transactions on* 5 (2006), Nr. 5, 536–547. [http://ieeexplore.ieee.org/xpls/abs\\_all.jsp?arnumber=1610595](http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1610595)
  - [16] KAEMARUNGSI, K.: Distribution of WLAN Received Signal Strength Indication for Indoor Location Determination. In: *2006 1st International Symposium on Wireless Pervasive Computing*, Institute of Electrical & Electronics Engineers (IEEE), 2006
  - [17] KEMPKE, Benjamin ; PANNUTO, Pat ; DUTTA, Prabal: PolyPoint: Guiding Indoor Quadrotors with Ultra-Wideband Localization. In: *Proceedings of the 2Nd International Workshop on Hot Topics in Wireless*. New York, NY, USA : ACM, 2015 (HotWireless '15). – ISBN 978-1-4503-3699-4, 16–20

- [18] LANZISERA, Steven ; LIN, David T. ; PISTER, Kristofer S.: RF time of flight ranging for wireless sensor network localization. In: *Intelligent Solutions in Embedded Systems, 2006 International Workshop on IEEE*, 2006, S. 1–12
- [19] LIM, Chang-Beom ; KANG, Sung-Hun ; CHO, Hyun-Hun ; PARK, Sin-Woo ; PARK, Joon-Goo: An Enhanced Indoor Localization Algorithm Based on IEEE 802.11 WLAN Using RSSI and Multiple Parameters. In: *2010 Fifth International Conference on Systems and Networks Communications*, Institute of Electrical & Electronics Engineers (IEEE), aug 2010
- [20] MAHFOUZ, Mohamed R. ; FATHY, Aly E. ; KUHN, Michael J. ; WANG, Yahzou: Recent trends and advances in UWB positioning. In: *Wireless Sensing, Local Positioning, and RFID, 2009. IMWS 2009. IEEE MTT-S International Microwave Workshop on IEEE*, 2009, S. 1–4
- [21] OPTITRACK.COM: *Build Your Own Motion Capture System - OptiTrack.* <http://www.optitrack.com/systems/#motive-tracker/flex-3/16>. – online @ 2015-12-11
- [22] PEI, Ling ; CHEN, Ruizhi ; LIU, Jingbin ; KUUSNIEMI, Heidi ; TEN-HUNEN, Tomi ; CHEN, Yuwei: Using inquiry-based Bluetooth RSSI probability distributions for indoor positioning. In: *Journal of Global Positioning Systems* 9 (2010), Nr. 2, 122–130. [http://www.researchgate.net/profile/Jingbin\\_Liu2/publication/228994195\\_Using\\_Inquiry-based\\_Bluetooth\\_RSSI\\_Probability\\_Distributions\\_for\\_Indoor\\_Positioning/links/0fcfd5072a423a6678000000.pdf](http://www.researchgate.net/profile/Jingbin_Liu2/publication/228994195_Using_Inquiry-based_Bluetooth_RSSI_Probability_Distributions_for_Indoor_Positioning/links/0fcfd5072a423a6678000000.pdf)
- [23] PRIYANTHA, Nissanka B.: *The cricket indoor location system*, Massachusetts Institute of Technology, Diss., 2005. <http://ahvaz.ist.unomaha.edu/azad/temp/sac/05-priyantha-localization-sensor-networks-coverage-thesis-good.pdf>
- [24] SMITH, Adam ; BALAKRISHNAN, Hari ; GORACZKO, Michel ; PRIYANTHA, Nissanka B.: Tracking Moving Devices with the Cricket Location System. In: *2nd International Conference on Mobile Systems, Applications and Services (Mobicys 2004)*. Boston, MA, June 2004
- [25] STOIANOVICI, Dan ; WHITCOMB, Louis L. ; ANDERSON, James H. ; TAYLOR, Russell H. ; KAVOUSSI, Louis R.: A modular surgical robotic system

## Bibliography

---

- for image guided percutaneous procedures. Version: 1998. <http://link.springer.com/chapter/10.1007/BFb0056225>. In: *Medical Image Computing and Computer-Assisted Intervention—MICCAI'98*. Springer, 1998, 404–410
- [26] WANG, Zheng ; MASTROGIACOMO, Luca ; FRANCESCHINI, Fiorenzo ; MAROPOULOS, Paul: Experimental comparison of dynamic tracking performance of iGPS and laser tracker. In: *The International Journal of Advanced Manufacturing Technology* 56 (2011), September, Nr. 1-4, 205–213. <http://dx.doi.org/10.1007/s00170-011-3166-0>. – DOI 10.1007/s00170-011-3166-0. – ISSN 0268-3768, 1433-3015
- [27] WINGEN, Neal T. ; LAI, Eric ; MOSER, Arnaud ; DE VRIES, Ronald ; SUBRAMANIAN, Ramaswamy: *Automatic upgradeable UART circuit arrangement*. Google Patents, 2004 <http://www.google.com/patents/US6742057>. – US Patent 6,742,057
- [28] WOODMAN, Oliver J. ; HARLE, Robert K.: Concurrent scheduling in the Active Bat location system.
- [29] WU, Jun ; ZHU, Jigui ; YANG, Linghui ; SHEN, Mengting ; XUE, Bin ; LIU, Zhexu: A highly accurate ultrasonic ranging method based on onset extraction and phase shift detection. In: *Measurement* 47 (2014), Januar, 433–441. <http://dx.doi.org/10.1016/j.measurement.2013.09.025>. – DOI 10.1016/j.measurement.2013.09.025. – ISSN 02632241