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Wireless Ranging in Swarm Robotics



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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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of figures in
Caption

1 Introduction

1.1 Motivation

The FINken project aims to create a swarm of autonomously flying quad-copters to research swarm intelligence behaviour on robots. Many algorithms in swarm intelligence are based on distance values. On this occasion it is important to find a sensor that is capable to measure distances and to integrate it into the FINken robots. An obvious choice for this distance is measuring the spacial distance in between the robots¹.

source

1.2 Requirements

There are basically three requirements for this 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 needs 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 a good idea as the copter already uses multiple ultrasonic sensors. If no measures are taken

¹ The mathematical distance-property might not actually need to be something as close to a physical property, but it is beneficial to be able to measure and watch the robots interacting with their physical environment.

to counteract medium access problems both sensors will disrupt each other to a point where the sensor values are completely useless. However this requirements is bendable to a certain degree. If there is interaction between copter and ranging sensors the copter might be changed to eliminate this interaction.

1.2.2 Integration of the Ranging Modules

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

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 in this scenario. 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

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

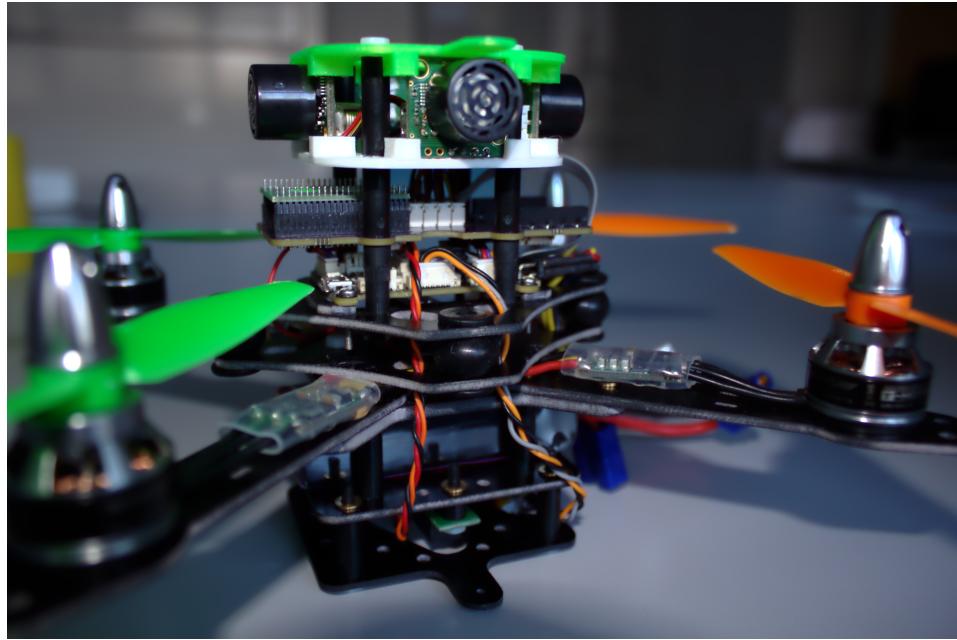


Figure 1.1: The FINken robot, revision 3

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.

überleitung

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° and its height is kept stable it is accelerating at about 1 m s^{-2} if the height stays the

kleine
störung->
rel. großer
effekt

same during that time. This means the copter reaches a velocity of over 2 m s^{-1} when travelling through the arena at this pretty small angle.

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 research the behaviour of the quadcopters if a certain task is assigned to the robot, e.g. finding the brightest spot.

foto

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 sensors needed for autonomous flight must not be disturbed by the other components 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 or the optical flow sensors are used, alternatively 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 strategy 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 its 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 sensors that are exclusively used for interaction.

To interact with its 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-beheaviour.

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 "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 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, alternativ 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

mehr fokus
auf andere
copter pro-
jekte

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 that use range measurements, however many of those positioning technologies are base on other principles than multilateration². [3]

keep it or
throw it
away?

1.4.1 Indoor Time of Flight

The obvious approach for replacing the GPS signal is to use a simmilar approach indoors.

The problem is that very short timespans have to be measured accurately, because radio waves are so damn fast. [12] states, that standard errors of 2.6 m_{RMS} and 1.8 m_{RMS} was measured in different indoor scenarios. With an operating area only 3m wide this approach is not suited for our robots.

wording

A project that looks more promising is decaWave. According to [11] the measurement error is generally under 1m and with filtering can be brought to below 15cm. The proposed method of filtering needs 27 measurements to compute one range value. However the decaWave project was unkown to us when we started looking for ranging possibilities so

wording

blabla

1.4.2 Cricket / Active Bat

A very clever approach to ranging is used by ranging solutions like cricket[16] and active bat[20]. RF-Signals travel at the speed of light and therefore you need to be able to measure very short timings in time of flight scenarios. Sound however travels at a speed much slower than radio waves. The same principle can be applied when you measuring the distance of a lightning strike by measuring the time between thunder and lightning. Cricket and Active Bat also measure the time difference an RF-signal and an ultrasound pulse need to

²The usual methods for positioning are: *multilateral*—which is what we are interested in because only ranging measurments 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.

travel from transmitter to receiver to calculate the range between two sensor nodes.

A bad side effect of using sound as medium to the ranging method is that there is an upper bound to the update frequency for all nodes sharing the medium (i.e. close enough to sense each other). [20] 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 or the sonar sensors needed to be replaced

accuracy /
price, moving
objects

Ultrasonic ranging on quadcopters is done by [8]

Another problem is the noise created by motors and propellers. The sound made by the quadcopters is not ending in the hearable spectrum but also extends to the ultrasound range. In conclusion ultrasound based ranging is a very neat approach that could be integrated into the FINken robots, but the current setup that already includes sonar sensors make this approach impractical.

1.4.3 RSSI-based ranging

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-based ranging is done for several different technologies: Bluetooth, WLAN, RFID – There are even approaches using maps created of different RSSI-ranging sources. http://www.gnss.com.au/JoGPS/v9n2/JoGPS_v9n2p122-130.pdf

quelle

quelle

quelle

quellify

typical
propaga-
tion pattern
picture

The main factor that rules out RSSI-based ranging is that radio-waves are not propagated equally in every direction. Antenna-orientation might have a much bigger impact on signal strength than distance. Additionally radio waves might be weakened when travelling through the FINken robots and by doing so passing wires and electronic components.

1.4.4 External Tracking

Most projects use external 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. This price is justified by the superior performance of this method.

This means tracking accuracy as well as the possibility to measure orientation. All that at a high update frequency.

A huge drawback to this method is that many components are used that need to be integrated into the environment and cannot be carried by the robots themselves. For swarm robotics this is not an ideal solution as using external tracking would mean communicating with some kind of centralized tracking interface-destroying the scalability and the principle of local interaction leading to global behaviour.

refs

research
performance
statistics
for ranging
solutions

ETH, track-
ing, sensorik
foo

price

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.

2 Concept

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 however we only had a precompiled library for the Atmel ranging modules. For the evaluation scenario those modules are quite useable, but there are better options available with the binaries for other hardware platforms. On the copters we want to use \$Module from dresden elektronik which is already integrated into the new hardware revision of the FINken robots.

exact name

The disadvantage of the Atmel sensors is that they are not designed for production use but as development platforms and therefore are quite big and heavy and not really suited to be used on the FINken quadcopters. It is possible however to build a similar hardware setup that is much smaller by using smaller packages of the same chips, leaving lots of unused PCB area and unused connectors.

2.1.2 Autopilot

The FINken robots use the LISA/MX autopilot board in hardware revision 2.1. This board is used for higher level auto pilot functions as well as pure stabilization—unlike other UAV projects where there are different units for stabilization control and higher level functions like pathfinding. This means that all sensors are connected to this board; every computation from evaluation of sensor input to the output of PWM signals to the motors controllers is done on this board.

2.2 Interconnect

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

2.2.1 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 wire¹ would be needed to connect autopilot and sensor.

2.2.2 UART

The "Universal Asynchronous Receiver/Transmitter"-Protocol uses two wires to establish communication between devices. [19]

The Disadvantage of UART-style Protocols is that it is a bidirectional connection. That two pins are needed on sender and receiver side and if another device should be connected two new pins are needed. On the Lisa/MX autopilot there are four dedicated UART connections that might be used, but already three of them are used.

2.2.3 SPI

6 Pins, Clocked, Chainable, DMA

¹Plus two wires for voltage supply

2.2.4 CAN bus

Would be ok, no can device yet, pins for canbus already in use, would be solvable, but not easy to implement on ranging nodes

2.2.5 I2C

I2C is a two wired bus protocol that can be used to connect multiple slave devices to one master device. 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. The autopilot board also supports to have two independent i2c-networks.

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

problem:
slaves can
block the
bus

3 Implementation

Somehow the sensordata needs to find its way into the control loops of the autopilot. We have established that i2c is the hardware solution to transmit the data.

Now it is important to pin down in which way the measurements get triggered and when and how the result is transmitted back.

3.1 Communication Protocol

There are two possible ways to talk to the sensor. You can define independent commands to start a measurement and retrieve data. The obvious disadvantage of this method is, that there is a bit of communication overhead and the master device won't read the data from the sensor as soon as it is possible—the master might even start a new measurement without even reading the result at all.

The other way to do things is that the slave device writes the data onto the bus as soon as it is arriving. This way of sending results however has disadvantages that are far worse than reading measurements a bit later and even missing some measurements. Those disadvantages are caused by the way i2c handles slave writes.

The sensor has different functions described by i2c-registers that can be written to by the master device. The registers and the format of the range response are described by *i2c_interface.h*.

Another design decision that has to be made is how the data structure for ranging results should look like. Obviously the measured distance needs to be included in the message, but instead of the original 32-Bit value only a 16-Bit value is used, as distances up to more than 60m can be expressed that way.

status, dqc,
range, ad-
dresses,
message id

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	I2C_SET_FREQ_STOP	set upper frequency
0xCD	SET_DIVERSITY	turn on/off antenna bdiversity

Table 3.1: Implemented I2C-Commands and Description

The dqc value also needs to be transmitted, as the sensor node can not decide in which way the values should be used by the master device, i.e. making application dependent filtering more accurate¹. In scenarios with multiple ranging nodes or remote ranging the addresses of both nodes taking part in the range measurement also need to be included into the message. This information enables the master device to assign the range values to the right pair of devices, even if one of the messages gets lost or the order of measurements changes.

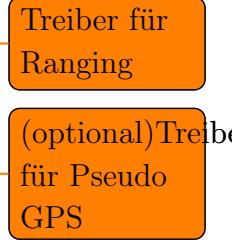
Depending on the setup the sensor nodes do not communicate measurement failures, but retransmit the old values again. As a consequence two more values should be transmitted: The status of the measurement and a message id. Those values enable the client to discard erroneous measurements and duplicate readings.

"TWI",
"Phillips-
I2C", "..."

¹ An application where the dqc-value is of much use is a Kalman-State-Filter, which could gain accuracy by using the dqc value to estimate the reliability of the range values.

3.2 Paparazzi Module for Ranging

Addressing is done using the unique aircraft id of the individual robots. Because the short addresses for the ranging nodes are 16 bit long and the aircraft ids are 8 bit values it is feasible to use a fixed prefix together with the ac-id as node addresses.



3.3 Python Scripts

For testing the sensor nodes and also for acquiring the data for evaluating the sensors I set up a RaspberryPi minicomputer as i2c master. Using this setup for testing has proven really effective even before integrating attaching the sensor nodes to one of the finken robots. Python might also be a very powerful tool to prototype mathematical processing of the sensor inputs like filtering and fusion of different ranging results.

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 continuous range readings from the unix shell and is mainly used to generate csv-files with ranging values.

4 Evaluation

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 platform is simply too 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 other sensors useless, in worst case crashing the copter.

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

measure

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
könnte :(

measure

4.1.3 Integration Test for Quadcopter

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 interdependend variables that influence ranging accuracy.

4.2.1 Frequency Selection

move to implementation?

The frequencys 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 serveral other technologies are using the same frequencys 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 then on frequencys 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). 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 frequencys a range of 2.480 GHz to 2.500 GHz has been chosen. All the frequencys in this range look quite simmilar 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 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 aviable channels in the frequency range and channel spacing are variables that can not be directly measured in our lab¹. 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 frequencys takes lots of labtime. It is not viable to measure all aviable combinations for those parameters.

Find out antenna measurements / calibrated antennas

wording

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

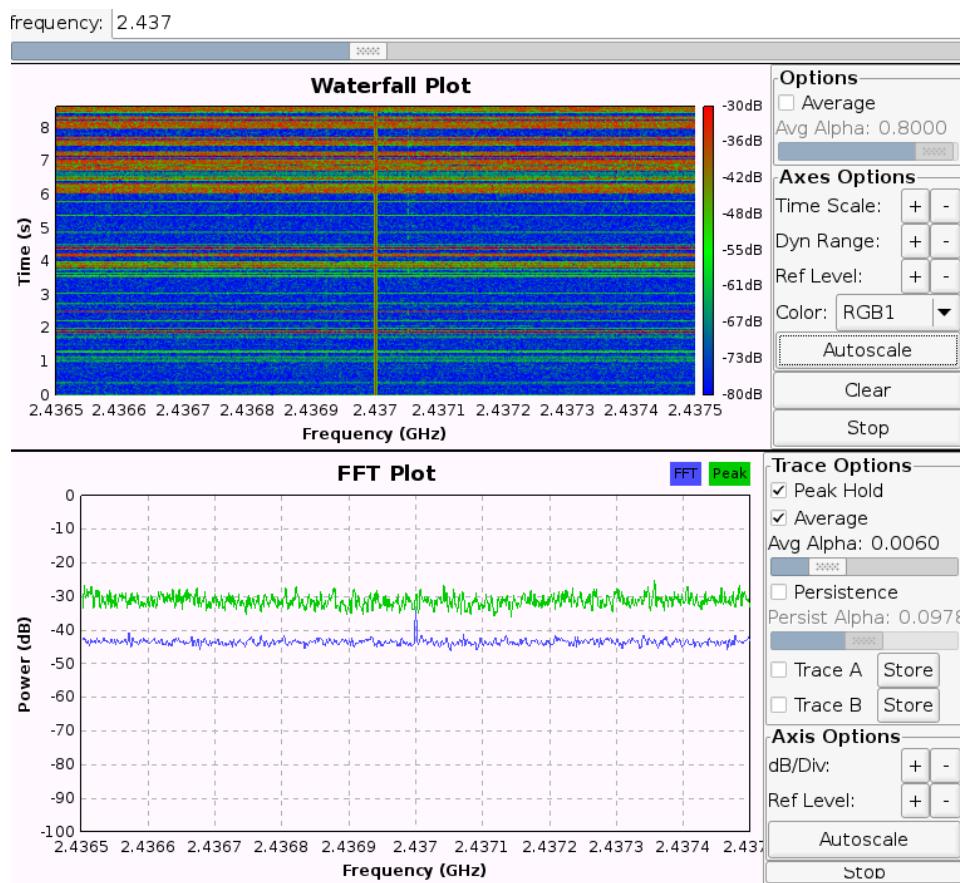


Figure 4.1: RF-Spectrum on 2.437 GHz

¹The 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.

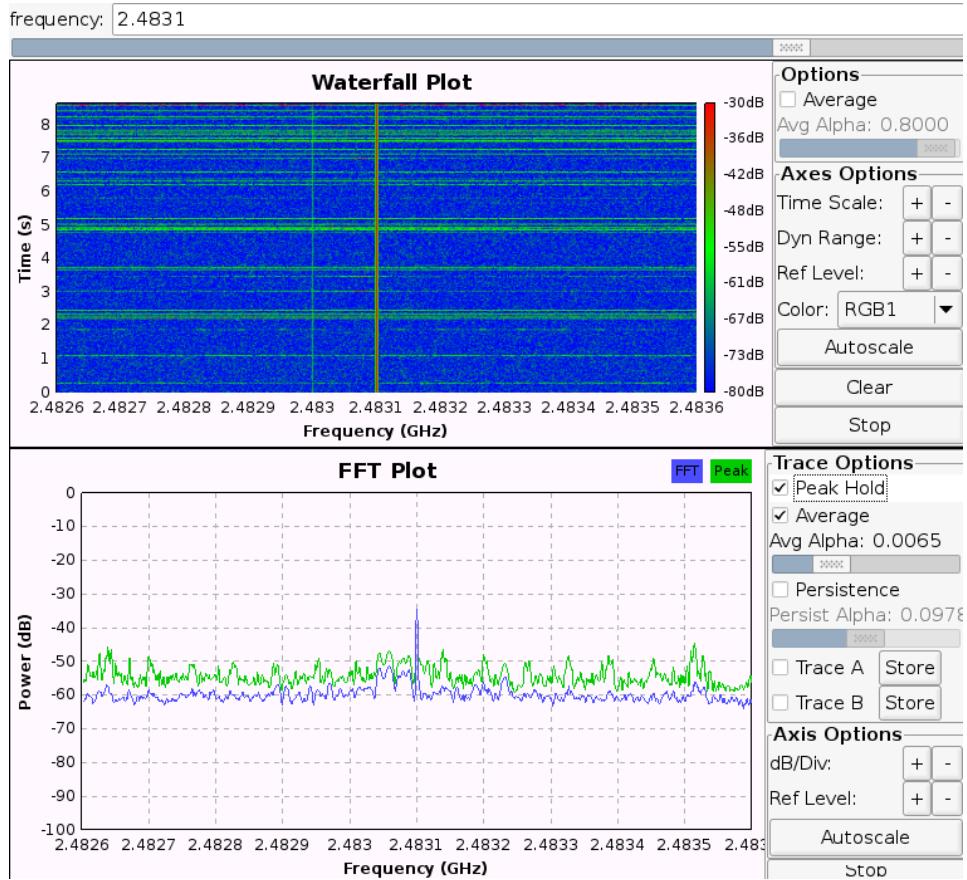


Figure 4.2: RF-Spectrum on 2.483 GHz

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

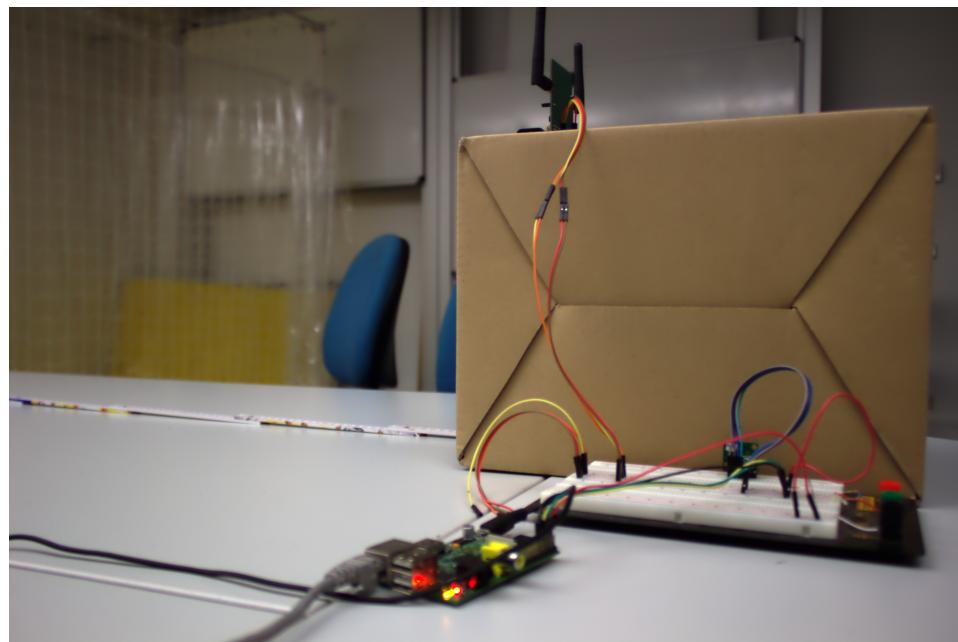


Figure 4.3: Measurement Setup

4.2.3 Influence of DQF on Range Values

One value the ranging api provides is the DQF²-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 1 m 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 1 m or 3 m distance the when the dqc is low the measured range is lower and if dqc is high the measured range is higher.

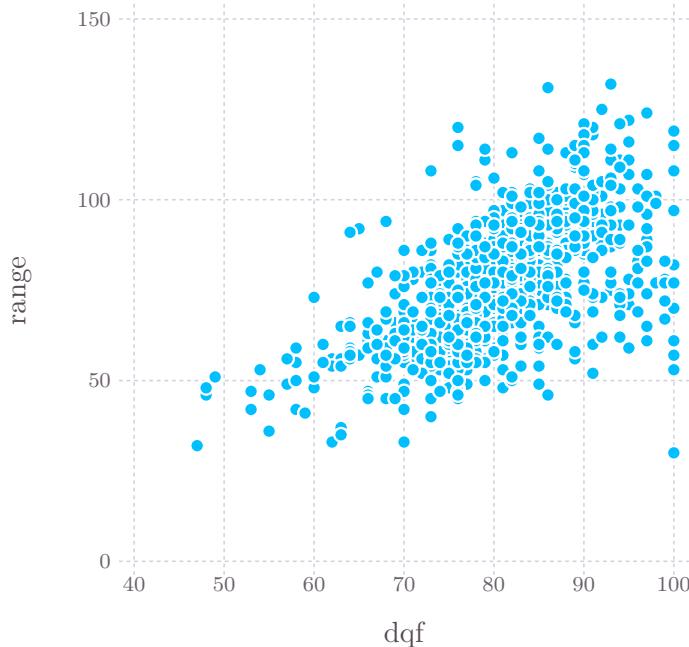


Figure 4.4: 1000 values measured at 1 m distance

²Data 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.

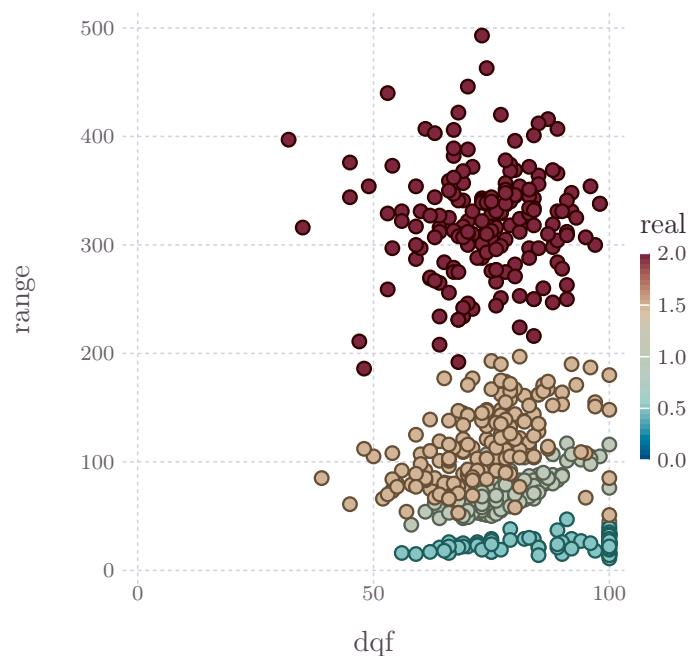


Figure 4.5: values measured at 0.5 m to 2 m real distance

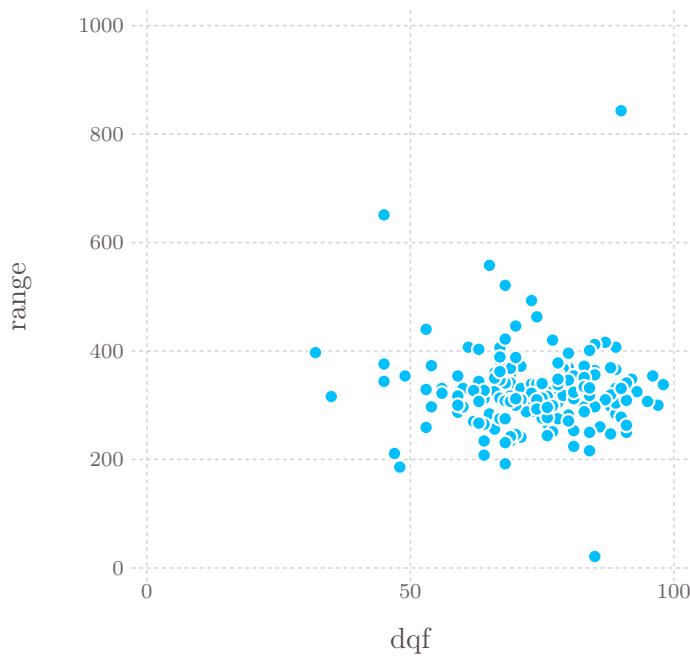


Figure 4.6: 100 values measured at 2 m distance

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 intervall 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.

prettyfy

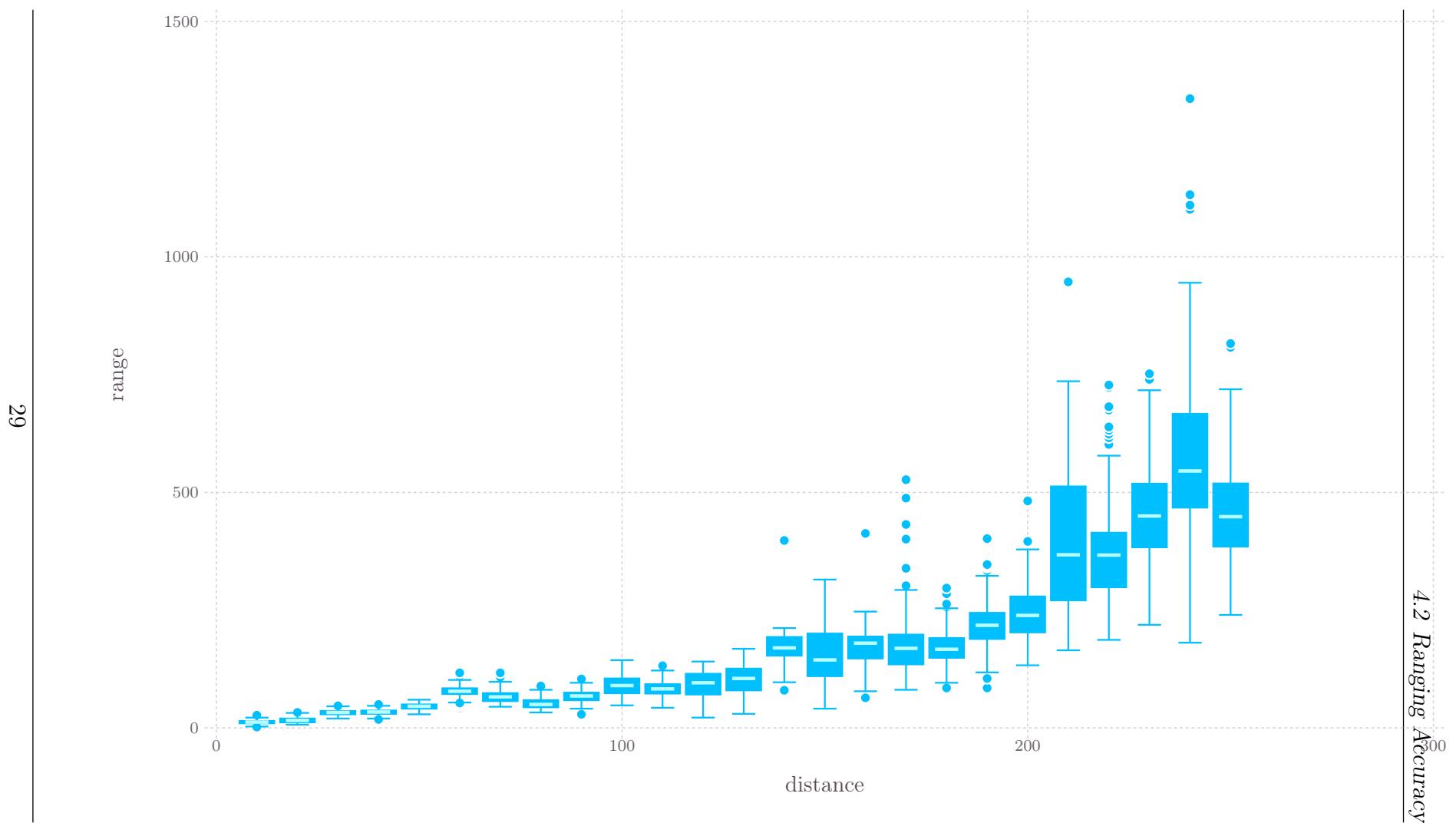


Figure 4.7: range values and real distance

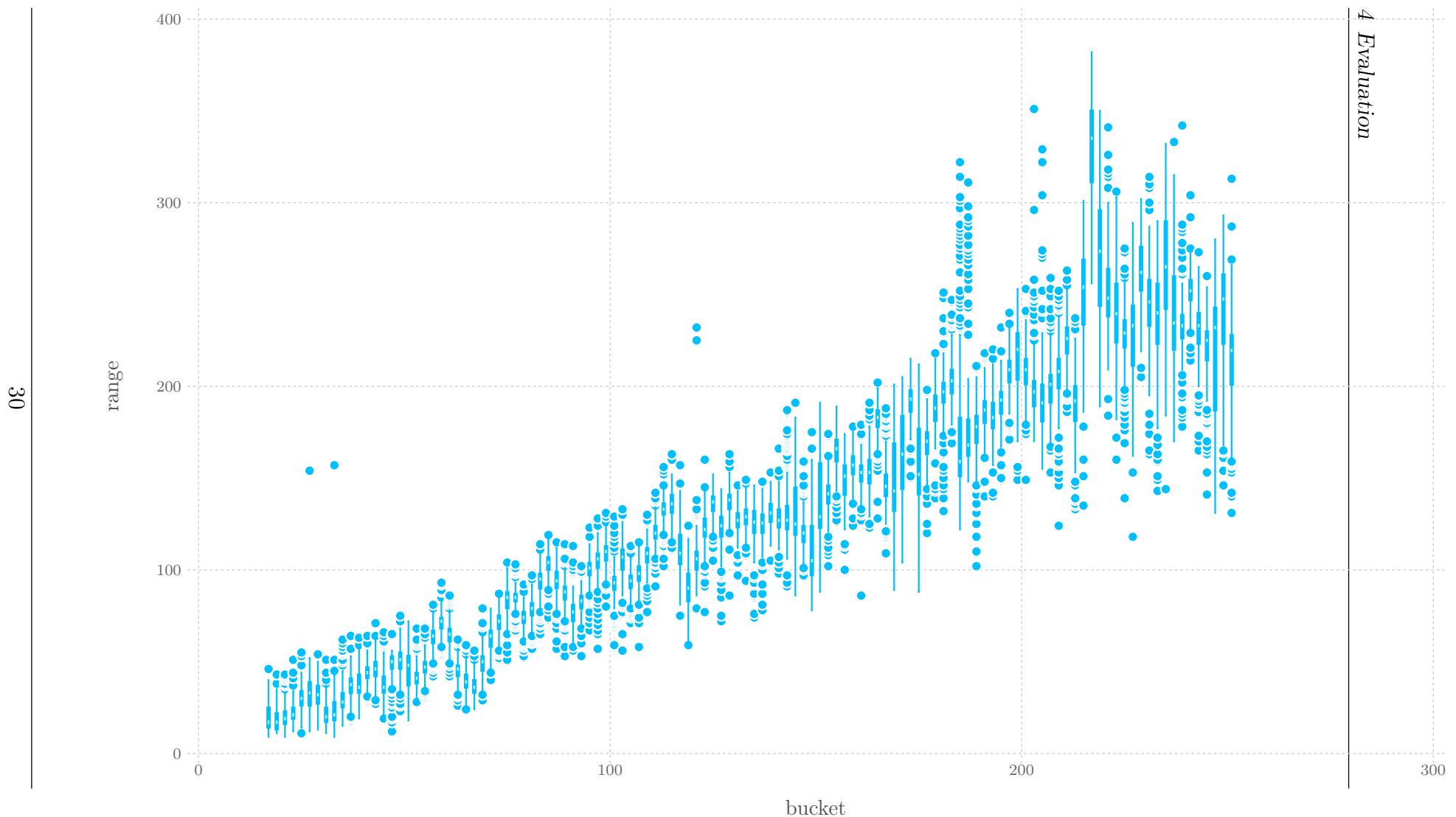


Figure 4.8: Range values with 2 cm resolution

4.2 Ranging Accuracy

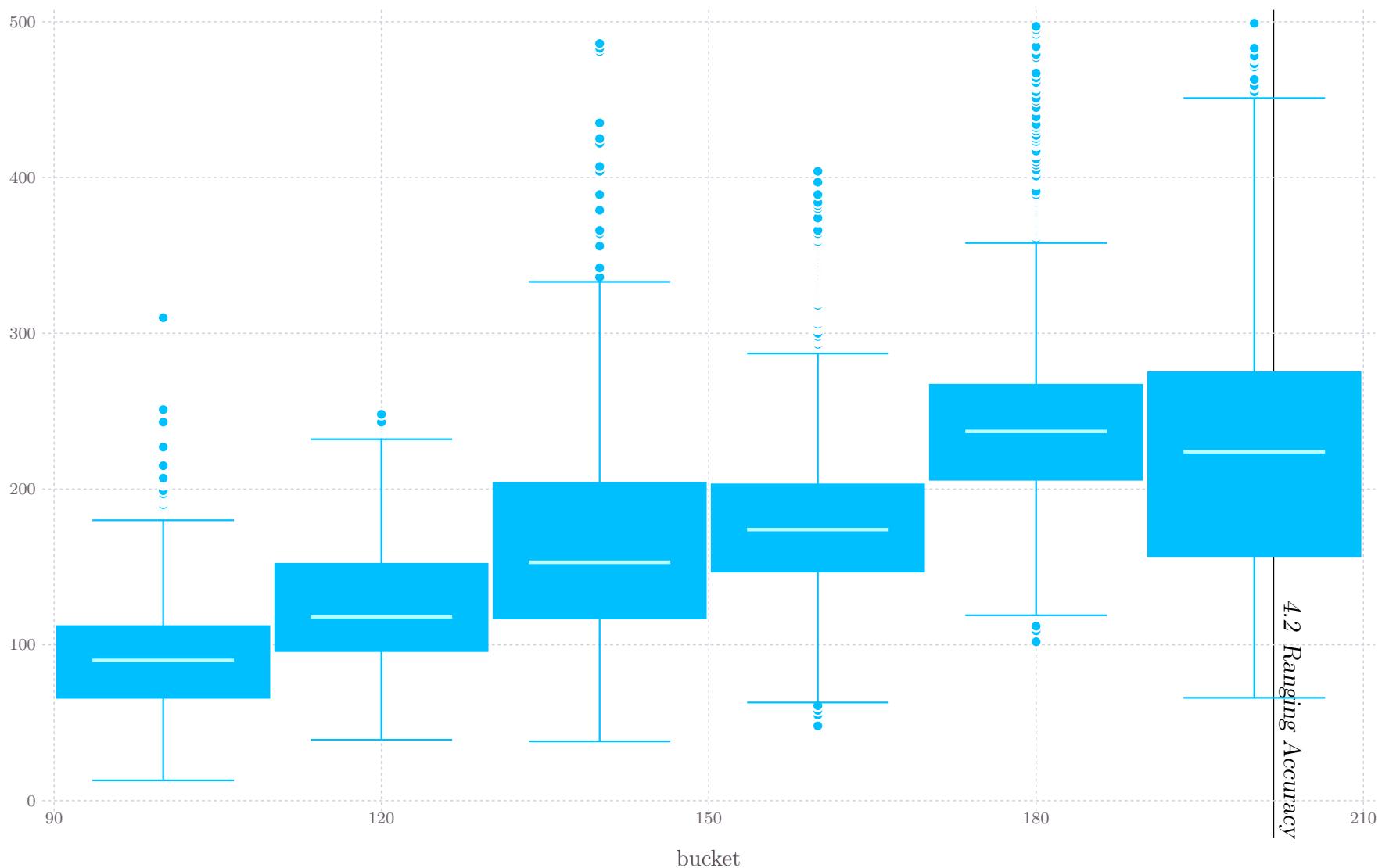


Figure 4.9: Range values with 1 cm resolution each bar represents all the values in the range, with bucket size of 20 cm

caption for
buckets
(wording)

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.

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.

However the lack of symmetry might be utilized.

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

plot, evaluate, spoiler alert: Nope!

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.

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.

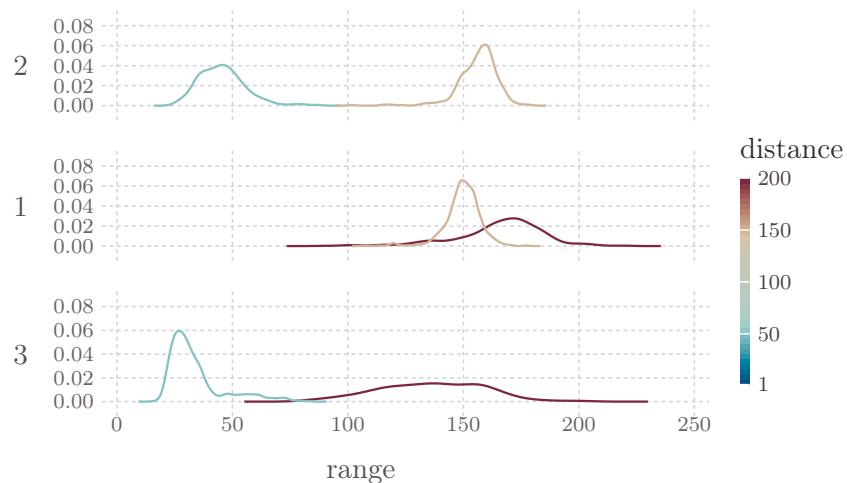


Figure 4.10: Density functions for 3 nodes, Nodes were placed in a straight line with numbers 1, 2, 3. Distance 1-2 was 150 cm, distance 2-3 was 50 cm.

4.4 Conclusion

-> unpersonal lingo

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

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.

wording

5 Future Work

5.1 Misc

find better caption

5.1.1 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.

filtering -> papers

5.1.2 Further Integration

integration testing, op-titrack

5.1.3 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

5.1.4 Distance Based Bounding Box

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.

5.2 Applications in Swarm Robotics

5.2.1 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.

5.2.2 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.

5.2.3 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

Bibliography

- [1] *Lisa/MX V2.1 Autopilot.* <http://1bitsquared.com/products/lisa-mx-autopilot>
- [2] *PaparazziUAV.* http://wiki.paparazziuav.org/wiki/Main_Page
- [3] *Multilateration.* <https://en.wikipedia.org/w/index.php?title=Multilateration&oldid=670629691>. Version: Juli 2015. – Page Version ID: 670629691
- [4] 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
- [5] 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
- [6] 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
- [7] CENTER FOR HISTORY AND NEW MEDIA: *Zotero Quick Start Guide.* http://zotero.org/support/quick_start_guide
- [8] 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

Bibliography

- [9] 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
- [10] 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
- [11] 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
- [12] 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
- [13] 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
- [14] PEI, Ling ; CHEN, Ruizhi ; LIU, Jingbin ; KUUSNIEMI, Heidi ; TENHUNEN, 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
- [15] 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>

- [16] 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
- [17] STOIANOVICI, Dan ; WHITCOMB, Louis L. ; ANDERSON, James H. ; TAYLOR, Russell H. ; KAVOUSSI, Louis R.: A modular surgical robotic system 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
- [18] 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
- [19] 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
- [20] WOODMAN, Oliver J. ; HARLE, Robert K.: Concurrent scheduling in the Active Bat location system.
- [21] 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

