Sebastian Mai

Wireless Ranging in Swarm Robotics

Some Department

Bachelor Thesis

Wireless Ranging in Swarm Robotics

Author:	Sebastian Mai	Your Term	The Year
Professor:	Your Professor		
Tutor:	Your Tutor		

Sebastian Mai: *Wireless Ranging in Swarm Robotics*
Bachelor Thesis, Otto-von-Guericke-Universität
Magdeburg, The Year.
Chair of Intelligent Systems- Some Department


Finken
Ranging
Evaluation
Result

Contents

List of Figures

1 Prior Art

1.1 The FINken Robot Platform

The FINken project aims to create a swarm of autonomously flying quadcopters to research swarm intelligence beheaviour 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.

source

1.1.1 Environment

Creating a swarm of flying robots is a rather difficult task. The environment for the FINken robots is created to protect the robots from mechanical damage and to function well with the sensors the robot uses.

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 coverd 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 assign a certain task to the robot, e.g. finding the brightest spot.

foto

1.1.2 Actuators and Dynamic

put this subchapter into introduction

Like most quadcopters the FINken 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 speed of each motor is controlled by an the LisaMX 2.1 autopilot-board[1] using the opensource autopilot firmware Paparazzi[2].

The robots are highly dynamic-the robots have enough acceleration to leave the operating environment in any possible direction. 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. Even if the high power of the motors is not utilized stability is a problem. If the copter is angled by only $6°$ and it's height is kept stable it is accelerating at about $1\,\mathrm{m\,s^{-2}}$

1.1.3 Sensor Concept

The sensors used by the FINken robots are usually used for two purposes: To enable the robots to fly autonomsly 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 autonoms flight must not be disturbed by anything else.

The flight dynamics of the FINken robots shall be as simple as possible. The robots shall be able to fly at a given height and navigate in x-y-direction to perform their given tasks. Highly dynamic maneuvers are possible for the airframe, but are not realizable with the sensor data we currently get.

ref to christophs ba

For flying autonomously two major problems have to be solved: 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 must 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 hard to get by. As a consequence implementing a position hold mode is quite a challenge. Assuming that a stable position can not be kept there is still something that can be done to fly for longer time periods. With an ultrasound distance sensor in each direction the robot can sense its surroundings and avoid any obstacles in its vicinity. An essential precondition for navigating around obstacles that way is a certian level of stability and avoiding highly dynamic maneuvers.

wording

Interaction

The FINken robots shall be able to do more than simply not crashing. 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 an environment a solution is necessary that works well in the laboratry. The environment of the robots shall be changed without changing the physical layout of the lab. An environmental factor that can be easily changed is the lighting of the flying area. In the swarmlab a projector can be used to affect the quadcopters. To measure the current lighting situation an rgb color sensor is mounted on top of the copter.

The range-sensor is also mainly used for interaction. Ranging values enable the FINken robots to implement attraction-repulsion-beheaviour.

1.1.4 Hardware interfering with ranging

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 measurments made by the new sensor.

Sonar Sensors Sonar sensors to measure distances of the nearest object in four directions (front, back, left, right)

Motors Four brushless motors that may cause RF-interfercene and noise

Telemetry BTLE-/Zigbee modules to exchange data with the ground station

RC-Control 2.4GHz based Radio Control to manually control the robots

fink3?

Supply Lithium polymer batteries with nominally 6.6V output voltage that is converted to 5V and 3.3V by the power distribution hardware

weight

payload

Payload The overall weight of the copter in the current configuration is about g with about g headroom for additional equipment

Size The copter has a rotor to rotor distance of 10cm, and a sensor tower that is about 4cm by 4cm wide to use the existing mounting holes would be favourable

1.2 Evaluation of Existing Ranging Solutions

mehr fokus auf andere copter projekte

There are some technologies that can be used for ranging, however the usual application for most of those technologies in research is positioning. For that reason it is interesting to search for positioning applications that use range measurements, however many of those positioning technologies are base on other principles than multilateration[1]. [3]

[1]The 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.

The usual technologies used for ranging are based on time of flight measurments, signal strength, optical tracking, and phase diffence measurments in signals.

1.2.1 Indor Time of Flight

The obvious approach for replacing the GPS signal that is aviable outdoors is to use a simmilar approach indoors. http://robotics.eecs.berkeley.edu/ pister/290Q/Papers/Location/Lanzisera%20RF%20TOF%20WISES06.pdf states, that an accuracy of $2.6m_{RMS}$ was achieved indoors. With an operating area only $2m$ wide this approach is not suited for our robots. However this research is focused on using cheap sensor-nodes.

quellify

find commercial solutions with better accuracy

http://www.researchgate.net/profile/Bardia_Alavi/publication/224315086_Measurement_and_
Based_Ranging_in_Indoor_Multipath_Environments/links/0912f50b396c340971000000.pdf

quellify

Another approach to provide an indoor GPS-like solution is iGPS. http://www.nikonmetrology.com/de_EU/Produkte/Grossvolumige-Messaufgaben/iGPS/iGPS however is not ranging-based but uses angulation as underlying technology and is therefore useless to us. * IGPS http://porto.polito.it/2438175/2/IJAMT_iGPS_and_LT.pdf

quellify

deka-wave

1.2.2 Cricket / Active Bat

A very clever approach to ranging is used by ranging solutions like cricket and active bat. 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 RF. Cricket and Active Bat use this to measure the time difference an RF-signal and an ultrasound pulse need to

Quelle, Quelle

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

thunderstorm and ligth-ning very very frightning

accuracy / price, mov-ing objects, medium access (number of nodes)

There are two big problems with this approach that stem from the current setup of the FINken-Robots. The FINken Robots use ultrasound sensors to measure the distances to nearby objects. Those technologies would interfere with the ultrasound sensors already used and a replacement would be needed.

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.

measure noise, PWM-frequency of speedcon-trollers

1.2.3 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 serveral 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

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

typical propaga-tion pattern picture

1.2.4 External Tracking

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

refs

With external tracking high accuracy for ranging and orientation can be

research performance statistics for ranging solutions achieved with a high update frequency.

ETH, tracking, sensorik foo

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 priciple of local interaction leading to global beheaviour.

price

1.2.5 Atmel RTB, Dresden Elektronik, Meterionic

2 Concept

2.1 Hardware

2.1.1 Ranging Hardware

There are several different possible hardware plattforms for the Atmel ranging software. At the time this thesis started however we only had a precompiled libary 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 plattforms. 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 plattforms 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 simmilar 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 levelfunctions 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 diffrent 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 wire[1] 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. [14]

[1] Plus two wires for voltage supply

The Disadvantage of UART-style Protocols is that it is a bidirectional connection. That two pins are needed on sender and reciever 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

2.2.4 CAN bus

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 optionalcolorsensor 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 triggert 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 disatvantage 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 event 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 disatvantages that ar e far worse then reading measurements a bit later and even missing some measurements. Those disatvantages 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*.

C_START_RANGING start ranging

_SET_I2C_ADDRESS set new i2c address

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

3.2 Paparazzi Module for Ranging

Treiber für Ranging

(optional)Treiber für Pseudo GPS

Addressing is done using the unique aircraft id of the indivdual robots. Because the short addresses for the ranging nodes are 16 bit long and the aircraft ids are 8 bit values it is feasable 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 aquiering the data for evaluating the sensors I set up a RapsberryPi 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 powerfull 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 continous 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 completly, 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

4.1.2 i2c errors per time

Another problem that may occure 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 derivate computed from the range value .

jaja, als ob man da was sinvolles ausrechnen könnte :(

measure

4.1.3 Integration Test for Quadcopter

4.2 Ranging Accuracy

4.2.1 Frequency Selection

The frequencys used by the ranging can be chosen. 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 subsection 4.2.1 there is an analysis on the frequency utilization on wifi channel 6. A download was started and then ended which is noticable in the waterfall plot.

Comparing the 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.

Figure 4.1: RF-Spectrum on 2.437 GHz

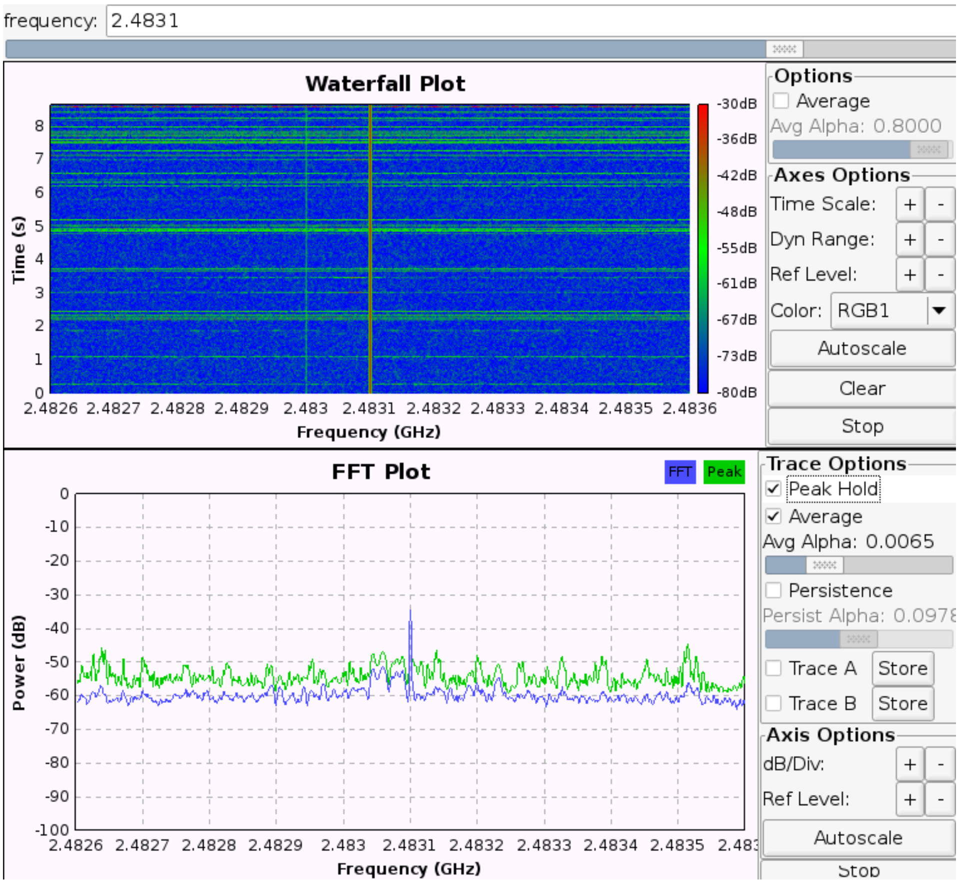

Figure 4.2: RF-Spectrum on 2.483 GHz

4.2.2 Influence of DQF on Range Values

One value the ranging api provides is the DQF[1]-value. It is reasonable to expect a huge amount of scatter for lower DQF values. As Figure 4.3 shows this is not how the range value behaves.

For the values measured with 1 m real distance we can see that the values meansered 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

[1]Data Quality Factor

taken at 1 m real distance it seams like we could be able to improve the range estimate by including the dqf value into the computation of the distance. To do that this behaviour would need to be stable accross different distances, i.e. no matter if the measurement is taken at 1 m or 3 m distance the when the dqf is low the measured range is lower and if dqf is high the measured range is higher.

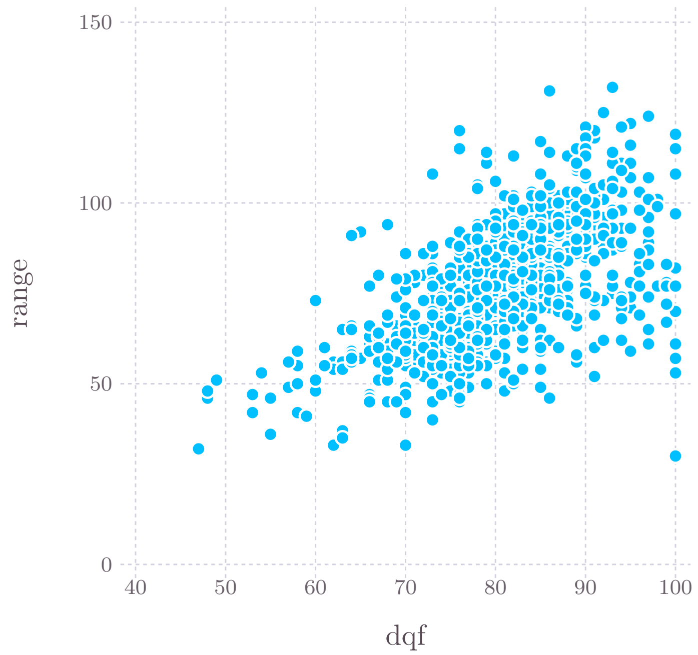

Figure 4.3: 1000 values measured at 1 m distance

Figure 4.4 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.

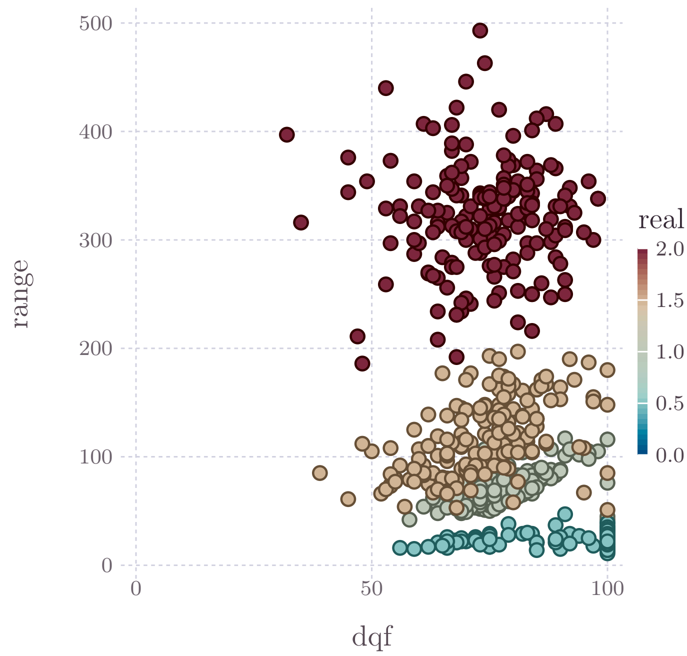

Figure 4.4: values measured at 0.5 m to 2 m real distance

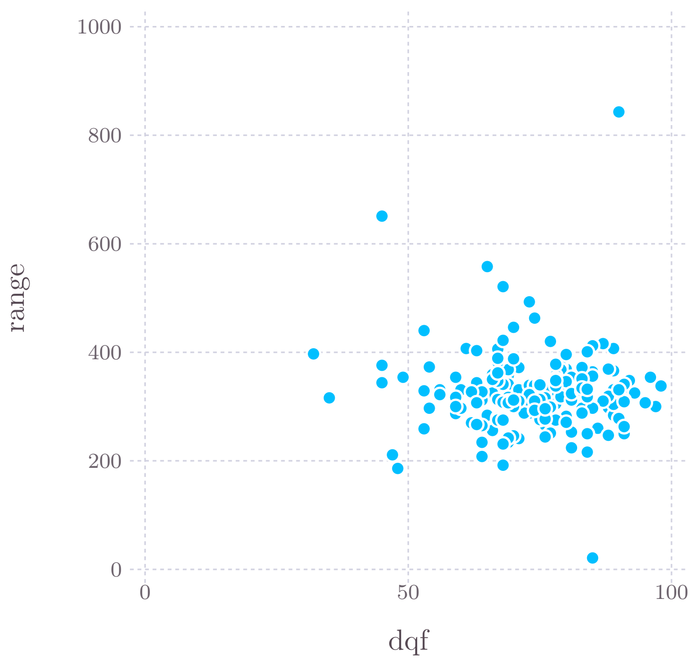

Figure 4.5: 100 values measured at 2 m distance

4.2.3 Influence of Distance

It is important to know how the ranging nodes behave at different distances. In Figure 4.6 this relationship is shown. The results are not what was hoped for when the hardware was selected. As you can see in Figure 4.6 the lower values yielded for any given distance might be in the intervall yielded for pretty much all distances. Additionaly 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

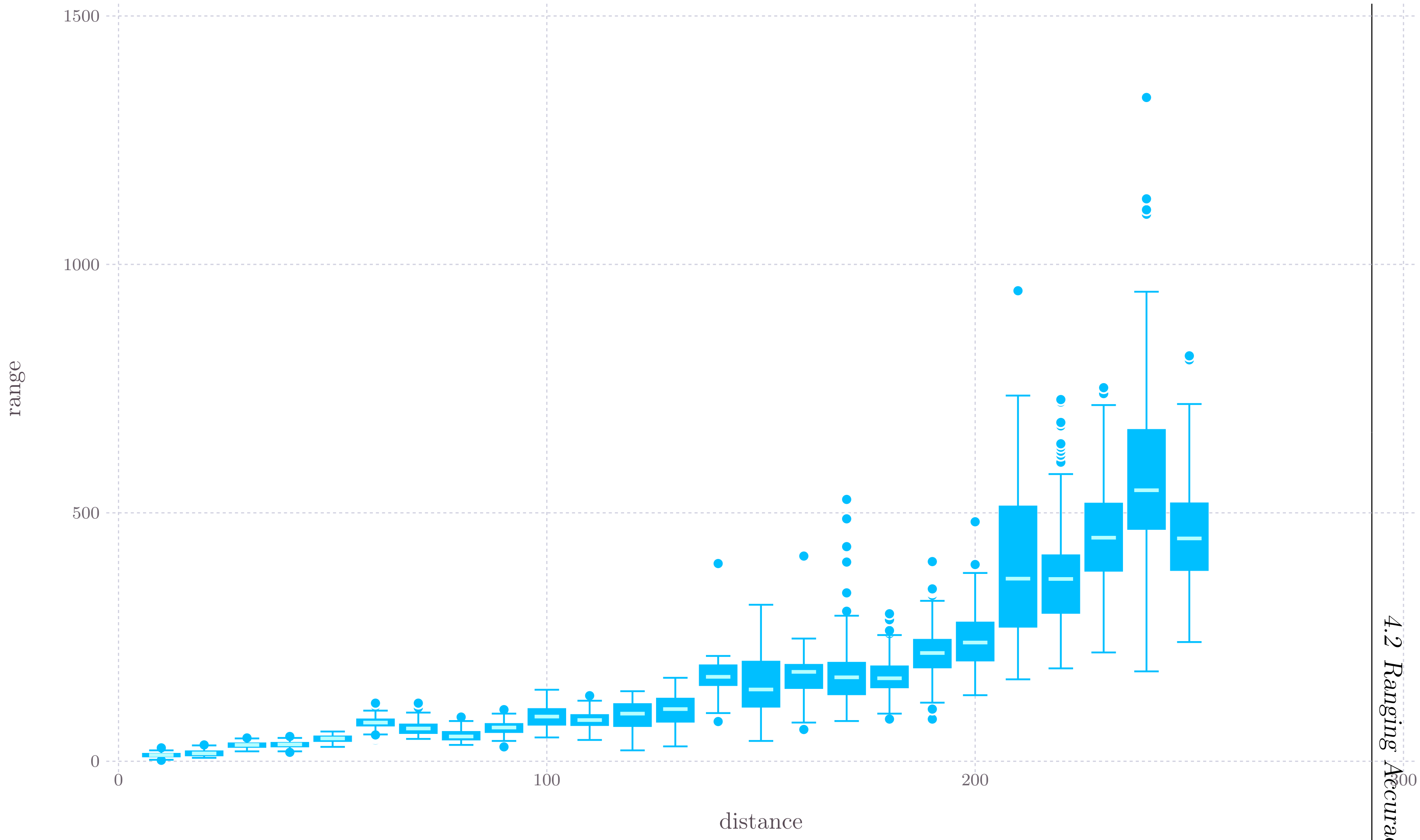

Figure 4.6: range values and real distance

4.2.4 Antenna Orientation

(diversity, no diversity) * (parallel, perpendicular)

4.2.5 Orientation of Devices

4.2.6 Moving Nodes

4.2.7 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 fullfill certian properties.

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

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

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

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

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

Of course the value measured by any real sensor will not completly 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 equvivalent in a mathematical sense.

4.3.2 Symmetry

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

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

measure, plot, evaluate

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.

4.4 Conclusion

5 Future Work

5.1 Formation Flying using Swarm Behaviour

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

5.1.1 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 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 reciever attatched.

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 aditional 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

Bibliography

[1] Lisa/MX V2.1 Autopilot.

[2] PaparazziUAV.

[3] Multilateration, July 2015. Page Version ID: 670629691.

[4] N.A. Alsindi, B. Alavi, and K. Pahlavan. Measurement and Modeling of Ultrawideband TOA-Based Ranging in Indoor Multipath Environments. *IEEE Transactions on Vehicular Technology*, 58(3):1046–1058, March 2009.

[5] Johann Borenstein, Hobart R. Everett, Liqiang Feng, and David Wehe. Mobile robot positioning-sensors and techniques. Technical report, DTIC Document, 1997.

[6] Pierre-Jean Bristeau, François Callou, David Vissiere, Nicolas Petit, and others. The navigation and control technology inside the ar. drone micro uav. In *18th IFAC world congress*, volume 18, pages 1477–1484, 2011.

[7] Center for History and New Media. Zotero Quick Start Guide.

[8] Slawomir Grzonka, Giorgio Grisetti, and Wolfram Burgard. Towards a navigation system for autonomous indoor flying. In *Robotics and Automation, 2009. ICRA'09. IEEE International Conference on*, pages 2878–2883. IEEE, 2009.

[9] Mike Hazas and Andy Hopper. Broadband ultrasonic location systems for improved indoor positioning. *Mobile Computing, IEEE Transactions on*, 5(5):536–547, 2006.

[10] Ling Pei, Ruizhi Chen, Jingbin Liu, Heidi Kuusniemi, Tomi Tenhunen, and Yuwei Chen. Using inquiry-based Bluetooth RSSI probability distributions for indoor positioning. *Journal of Global Positioning Systems*, 9(2):122–130, 2010.

[11] Nissanka Bodhi Priyantha. *The cricket indoor location system.* PhD thesis, Massachusetts Institute of Technology, 2005.

[12] Dan Stoianovici, Louis L. Whitcomb, James H. Anderson, Russell H. Taylor, and Louis R. Kavoussi. A modular surgical robotic system for image guided percutaneous procedures. In *Medical Image Computing and Computer-Assisted Interventation—MICCAI'98*, pages 404–410. Springer, 1998.

[13] Zheng Wang, Luca Mastrogiacomo, Fiorenzo Franceschini, and Paul Maropoulos. Experimental comparison of dynamic tracking performance of iGPS and laser tracker. *The International Journal of Advanced Manufacturing Technology*, 56(1-4):205–213, September 2011.

[14] Neal T. Wingen, Eric Lai, Arnaud Moser, Ronald De Vries, and Ramaswamy Subramanian. *Automatic upgradeable UART circuit arrangement.* Google Patents, May 2004. US Patent 6,742,057.

[15] Jun Wu, Jigui Zhu, Linghui Yang, Mengting Shen, Bin Xue, and Zhexu Liu. A highly accurate ultrasonic ranging method based on onset extraction and phase shift detection. *Measurement*, 47:433–441, January 2014.