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Christoph Steup, Sebastian Mai, and Sanaz Mostaghim

Abstract This paper presents a new platform for evaluation of swarms of aerial indoor robots which do not need external positioning systems. The major goal is to offer a test bed for both simulation and their counterpart in real tests. The paper addresses three main parts of the platform: the copters, the simulation and the test arena. The goal is to deliver a detailed description about the minimum required features for single aerial robots which can be used in the platform and are able to perform a swarm behaviour. Our proposed model for the aerial robots and the arena are being tested using a swarm behaviour both in physics-based simulation and real tests have been performed. While the simulation is an appropriate environment for testing the algorithms and the off-line behaviours in a swarm, real tests are necessary to reveal difficulties like cross-talk between the copters and the impact of the environment on the robots.

Key words: swarm robotics, quadcopter, autonomous behaviour

1 Introduction

Quadcopters are gaining increasing popularity in different fields of industry because of their flexibility and low price. They are used to ease inspection of buildings, provide impressive perspectives in sport events or movies. In almost all of these applications, the copters are manually controlled by remote devices. In addition the sensory data is evaluated by hand and typically only one single copter is used. In the scientific community quadcopters are already one step ahead. The paparazzi project [6] provides software to build

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autonomous airborne vehicles following pre-scripted trajectories to gather e. g. meteorological data [11]. However, these are designed to rely on GPS for localization and consequently for their autonomous behaviour. This disables them to be used in indoor environments or areas with unreliable GPS reception. Other platforms use external positioning systems which cannot be always practical in real applications.

The goal of this paper is to introduce a test bed to project theoretical swarm robotics algorithms to a platform for autonomous aerial robots. The research in the area of swarm robotics develops methodologies for autonomous behaviour of individuals which can adapt themselves to the dynamics of the environment and are robust against failures. Our proposed platform does not need any external infrastructure, especially no external localization or computational resources. Additionally, we aim to gain the benefits provided by swarm robotics such as scalability, robustness against failures, adaptation to the environment and spatial distribution.

The proposed platform captures the required features for a swarm of autonomous aerial copters both in simulation and real-world tests. It provides full access to all sensor data and additional external position estimations to enable an easy evaluation of algorithms and swarm behaviours. Additionally, the developed platform provides a baseline system to implement new applications like explorative mapping, indoor logistics and even autonomous copter racing. The experiments are validated using the theory of swarm formation in simulation and real tests. The results show that while the simulation can deliver stable behaviours for any number of copters, the real copters do not scale as well.

This paper is organized as follows. Section II is dedicated to related works. In Section III, we introduce the so-called FINken platform which includes the description of the copters and the simulation environment. Section IV includes the evaluation using the concepts of swarm formation in simulation and real-world tests. Section V concludes the paper and provides directions for future work.

2 State of the Art

The literature about swarm robotics is very rich in terms of algorithms for navigation, search, planning and formation. Several projects have dedicated a large amount of research on swarm robotics such as Swarm-bots [4], I-SWARM [15], SFly (swarm of flying micro-robots) [1], RoboBee [19] and Swarmanoid[1]. [3] provides a very detailed overview of the literature from the swarm engineering point of view. Swarm engineering is an emerging discipline

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[1] http://www.swarmanoid.org

that aims at defining systematic and well founded procedures for modelling, designing and realizing a swarm robotics system.

Different to ground robots, aerial robots have significantly different dynamics, require substantially more energy to locomote [12, 16], and the small payload entails reduced sensing and processing capabilities. In the literature, [17] developed an algorithm for indoor aerial swarm search that exploited the ability of aerial robots to attach to ceilings, saving energy as proposed by [12]. [16] continued their previous work and proposed a novel strategy that controls the density of aerial robots. As for the localization, there are attempts to use external positioning systems. Using external tracking and computations are proposed by [8] and [14] for aerial robotic systems. Indoor localization methods can rely on relative positioning systems using anchor nodes [10].

Swarm aggregation has also been studied in theoretical swarm intelligence (e. g. [5]) and swarm robotics using ground robots [3]. [5] proposed to use potential functions to achieve stable formations in swarms. [7] proposes an approach which is based on the potential functions and uses the relative positions of two neighbouring agents and hence does not require an external positioning system. In the context of aerial robots, swarm formation have been developed for outdoor applications using GPS by [18] in which the authors propose the first decentralized multi-copter flock which is able to perform stable autonomous outdoor flight with up to 10 flying agents. In their work the flying robots navigate themselves relatively based on information from others in their neighbourhood. However, the system utilises the advantage of GPS receivers and wireless modules for sharing the positional information locally.

3 The FINken Platform

In this section, we propose the so called FINken platform[2], which is designed to be used as a test bed for a scalable set of autonomous quadcopters and is well suited for indoor applications. In general, our goal is to enable a rapid-prototyping development and evaluation of swarm-based algorithms to enable cooperative behaviour and load balancing between the copters. This platform provides realistic models for sensors, communication and energy consumption and is aimed to build a bridge between the real copters and their virtual counterpart. The generic architecture of the test bed is visualized in Figure 1a. In addition to the test arena for the copters, the platform consists of a physics-based simulation of the copters for rapid prototyping and scalability analysis.

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[2] The FINken platform is developed at the SwarmLab of the Otto von Guericke University of Magdeburg, Germany (www.is.ovgu.de).

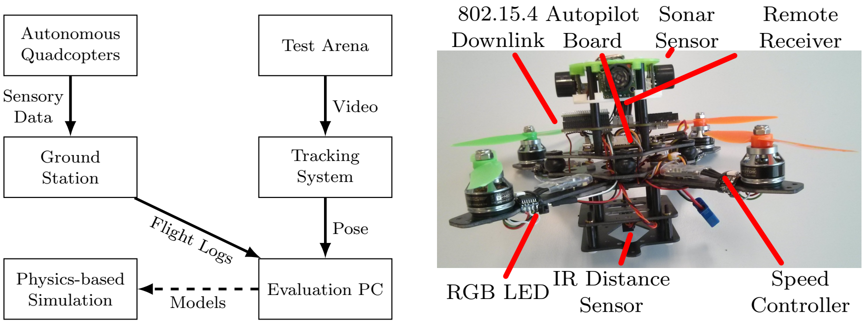

Fig. 1: iOverview of the FINken test bed for swarm robotics on the left side and the components of a single FINken copter on the right side.

The copters are built to enable a fully autonomous behaviour independent of any laboratory equipment and can be equipped with various sensors. This enables the evaluation of a broad range of algorithms and their assumptions on behaviours and sensory data. In our platform the sensory data from the copters is sent to a ground station only for evaluation purposes. Additionally, we can evaluate the behaviour of the copters by using a camera-based tracking system that is connected to the evaluation PC. The tracking system uses ROS as backend for video processing and pose estimation.

The focus on indoor usage eases the development and increases the repeatability of the conducted experiments. The lack of GPS reception and stable magnetic fields in the arena compels us to find new solutions to estimate the state of the copters. The physics-based simulation enables us to validate algorithms (e. g. online-learning) without breaking hardware. It is used to tune the parameters for certain behaviours and test the models in off-line mode in realistic environments.

3.1 Copter and Arena Description

Quadcopters are typically limited in size, load-capacity and power storage, the sensor payload and flight times are constrained by those factors. To counteract these limitations, the quadcopters in this platform called *FINkens*, are set up with powerful motors and large batteries. They are designed to fly in an arena of 4 m × 3 m, while maintaining a fixed height of up to 1.2 m (limited by the range of the height sensor). The arena is surrounded by ultrasound reflecting foils (like curtains) and nets to protect human spectators. Other projects that are performed in similar environments usually optimise the weight, sacrificing the independence of their copters from ground-components. This is usually done by utilising external tracking systems and outsourcing computing power to ground based servers [8]. For the purpose of autonomous operation, the FINkens require more sensors than typical copters. Four ultrasounds distance sensors and one IR-distance sensor are used for wall-avoidance and height control as shown in Figure 1b. The sonars are chosen because they provide reliable wide angle detection and the IR sensor provides fast response times and easy integration.

The current configuration of the FINken consists of:

- X-frame with 200 mm diagonal motor distance
- Li-Po Battery for 10 min flight (3 Cells, 900 mAh)
- Motors: MN1804-20: 2400 kV, max 10 A, 5×3” Propellers
- Overall weight of 350 g
- Embedded autopilot including 10-Axis-IMU (Paparazzi Lisa/MX 2.1)
- RC-Control with 2.4 GHz spectrum protocol
- 802.15.4 based communication
- SD-Card logging via SPI
- IR-Height Sensor (Sharp GP2Y0A60SZLF)
- Ultrasound-Object Sensors (Max-Botix MB1232)

The copter is programmed with our fork[3] of the Paparazzi autopilot framework [6]. The changes include additional sensors and the adaptation to the autonomous indoor use-case. Hence, our version of the software does not use GPS and implements object evasion with ultrasound as well as dedicated height control using a distance to ground sensor. We have developed two new modes of flight: Mixed-Manual mode and Wall-Avoid mode. In Mixed-Manual mode the copter is controlling thrust and yaw axis by itself, pitch and roll axis need to be controlled by the pilot via RC-commands. This modus operandi is used for calibration and in most manual flight scenarios, as it is much easier to control the copter in Mixed-Manual mode than in fully manual flight. The Wall-Avoid mode allows fully autonomous flight. The copter is controllable by the algorithms or a remote control device, as long as it can keep a safe distance to all objects sensed by the ultrasound sensors. If an object is detected, the copter is autonomously repelled enabling a stable baseline behaviour.

3.2 Physics-based Simulation

Among the available simulation frameworks for quadcopters such as JSBSim [2], ROS/Gazeebo [9] and V-REP [13], we selected V-REP [13]. The advantages of V-REP are the easy extension to a swarm of aircrafts and the set of available models for various sensors. V-REP uses a physics-based simulation

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[3] Available online at https://github.com/ovgu-FINken/paparazzi

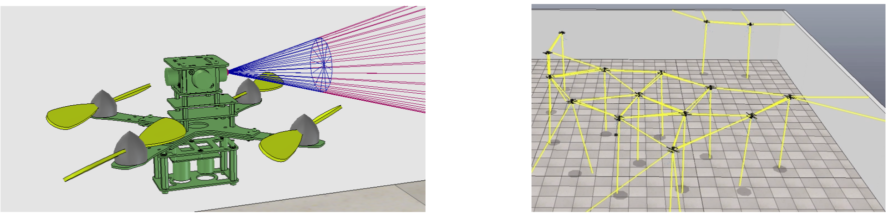


Fig. 2: Screenshot of the CAD-Model of FINken used in the simulation (left). Swarm of FINKens (right), the lines indicate the sensory data.

of rigid bodies. To implement quadcopters and their behaviour, we modify an existing quadcopter model with the CAD Model (see Figure 2) of our FINken and adapt the parameters to fit our platform. The CAD model is used for dynamic simulations i. e. computation of forces resulting in different behaviours as well as for collision avoidance with the environment and other objects including other copters. We use one central V-REP instance for the whole swarm to enable a consistent view on the environment by all copters. Our current simulation environments contain typical indoor objects like walls, and convex objects like boxes.

The simulated copters are controlled through their pitch, roll and yaw angles and the applied thrust, exactly as their real counterparts are. Since the real copters already contain autonomous height control a similar controller is implemented for the virtual ones. We modelled the sensory equipment using V-REP's proximity sensor system, which we parameterised according to the used real sensors. Additionally, we evaluate the noise model of the sonar distance sensors and apply it to the perfect virtual distance values. For performance reasons the simulation currently disregards air flow interaction between the copters. An evaluation showed that this is valid unless the copters are closer to each other than one meter.

3.3 Swarm behaviour

We take the concept of swarm aggregation using an almost linear attraction and non-linear repulsion potential function between the copters [5]. The attraction and repulsion can be described for two copters i and j as follows:

$$\mathbf{f}^i_{i,j}(t) = \begin{pmatrix} \varDelta x \\ \varDelta y \end{pmatrix} = -\left(a - b \cdot e^{\frac{-|\mathbf{D}_{ij}(t)|}{c}}\right) \cdot \mathbf{D}_{ij}(t) \tag{1}$$

$$\mathbf{D}_{ij}(t) = \begin{cases} (d_{F_i}(t) - d_{B_i}(t)) \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} & \text{if } j \text{ in range of } B_i \text{ or } F_i \\ (d_{L_i}(t) - d_{R_i}(t)) \cdot \begin{pmatrix} 0 \\ 1 \end{pmatrix} & \text{if } j \text{ in range of } R_i \text{ or } L_i \end{cases} \tag{2}$$

where $\mathbf{f}^i_{i,j}(t)$ denotes the vector of the negative of the gradient of the potential function from the perspective of i with x_i and y_i coordinates. $\mathbf{D}_{ij}(t)$ is a vector distance between the two copters i and j at time t depending on the output $d_{[F,R,B,L]_i}$ of one of the four sonar sensors of the copter i: Front (F_i), Right (R_i), Back (B_i) or Left (L_i). If a sonar does not detect anything it will output the maximum detection distance of $3m$. We consider discrete time and measure the new position for one time step i. e. $t+1$. a, b and c are constant values. For the experiments of the platform, we choose $a = 0$ and focus solely on repulsion. The other parameters are chosen as $b = 4$ and $c = 1.5$. These values yield repulsion to a distance of about 1.20 m. For a swarm behavior with > 2 copters, the copters move for one time step by considering the Equation (1) and (2):

$$\begin{pmatrix} x_i(t+1) \\ y_i(t+1) \end{pmatrix} = \begin{pmatrix} x_i(t) \\ y_i(t) \end{pmatrix} + \sum_{j=1, j \neq i}^{M} \mathbf{f}^i_{i,j}(t) \tag{3}$$

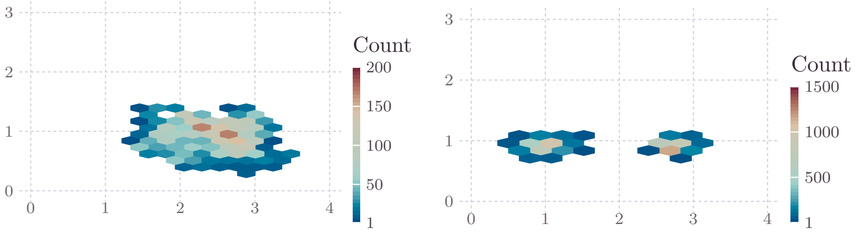
Here M denotes the number of detected copters in the vicinity of i.

4 Evaluation

In order to evaluate the proposed test bed, we analyse the behaviour of the copters both in simulation and real test by using a swarm behaviour:

Simulation Test: Following our rapid-prototyping approach, we evaluate the swarm behaviour first in simulation. We present the results for (1) one single copter and (2) two copters in the arena. The arena is modelled exactly as the real one with a fixed 4×3 m space (this defines the coordinate positions ranging [0, 4] for x and [0, 3] for y) and a height of 3.5 m. In the simulation, the distance sensors are configured to have a zero-mean Gaussian noise with a standard derivation of 0.05 m. The simulated copter has no access to its global position and could only change its pitch, roll, yaw and thrust values similar to the real copters. We let the simulation run for approximately 90 seconds for all the experiments.

The initial coordinated for positions are selected to be as (3, 1) for the experiment (1) and (1, 1) and (3, 1) for experiment (2). Figure 3 illustrate a heat-map of the positions of the copters over 90 seconds with sampling



(a) Single Copter (b) Multi Copter

Fig. 3: Heat-map visualizing the position (in x and y coordinates) of the copters (in the arena of size 4 m × 3 m) in the single copter (left) and two copters simulation scenarios (right).

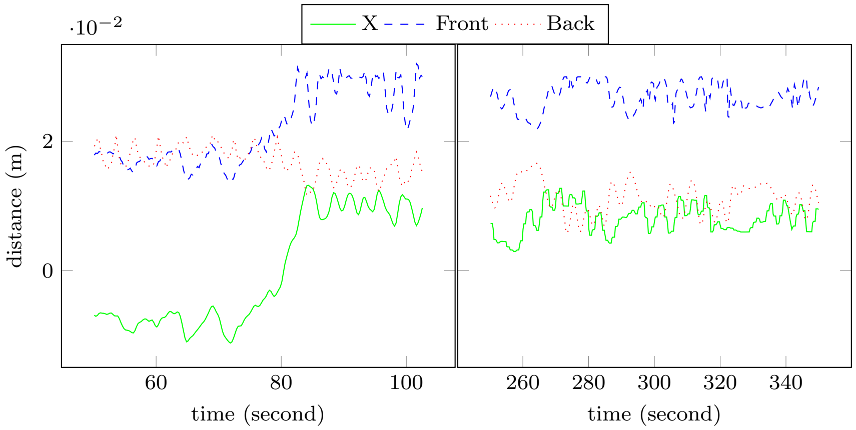
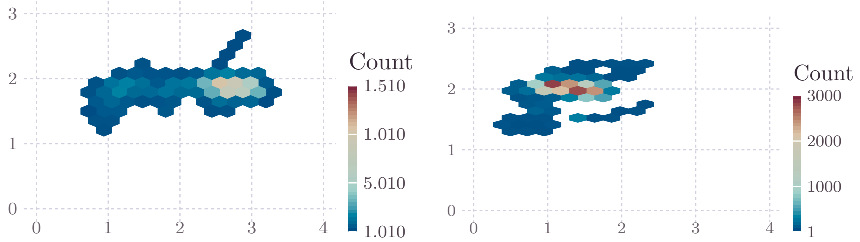


Fig. 4: Behaviour of a single copter in the arena. The left graph shows the simulated behaviour, while the right one shows the real behaviour.

rate of 40 HZ. We observe that in both experiments the copters are mainly moving close to the initial positions and deliver a stable movement.

Figure 4 (left graph) shows the behaviour of one simulated copter along the X-axis. Depending on the position in the arena the copter measures distances to front and back and controls its position accordingly. We observe that even though the sonar readings are noisy the copter behaves stably as expected. The above experiments using the physics-based simulation indicate that a swarm of two copters can stably fly in the arena even with noisy sensor measurements and no access to global positioning information.

Real-World Test: Similar to the experiments in the simulation, multiple real copters are tested in the arena. The behaviour of each copter is tracked using its on-board sensory equipment transmitted to a ground station using the 802.15.4 link at 38400 Baud. The data transmitted by the copter



(a) Single Copter (b) Multi Copter

Fig. 5: Heat-map of the positions (in x and y coordinates) of a single copter flying fully autonomously in Wall-Avoid mode (left) and together with a manually controlled copter (not shown here) as in Experiment 3 (right).

contains its state information including attitude, distances, acceleration and turn rates. Additionally, we use the camera-based tracking system to evaluate the movements with high accuracy. The experiments are performed for about 9 minutes and sampling frequency of the tracking systems is 50 HZ. We conduct the following four experiments.

Experiment 1: This experiment is dedicated to analyse the behaviour of one single autonomous copter and delivers the basic behaviour as expected by the simulation. We observe that the copter can reliably avoid the other "swarm entities", which are in this case the walls of the arena. Since no particular control command is sent to the copter, it starts with a random movement within the arena as illustrated in Figure 5 (left graph). Here the copter has the initial position of (1.9, 1.6). The copter can autonomously stay in the middle of the arena and avoid the walls by 1.20 m. The basic behaviour can be additionally observed in Figure 4 (right graph), which shows the values of the distance sensors in X-Axis together with the resulting attitude of the copter.

Experiment 2: The second experiment is meant to evaluate the behaviour of two copters flying autonomously in the swarm behaviour mode. The experiment shows a very strong instability of the copters as they moved erratically. One important observation is that most of the times the copters crash in the walls, but do not collide with each other. There could be two possible explanations for this behaviour:

1. Strong interactions between the copters caused by air flow
2. Disturbance of sensory data of one copter by the other

To identify the problem, we perform Experiments 3 and 4:

Experiment 3: In this experiment, one copter is flying autonomously and the other one manually. This is meant to give us an estimation of the airflow-based interaction between copters. To this end, one copter was controlled partially manual, with deactivated distance sensors. The height of the copter

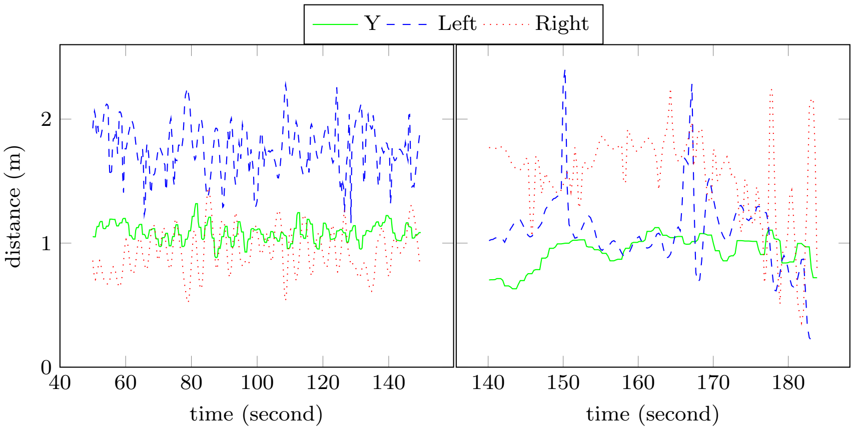


Fig. 6: Visualization of the y position, left and right sonar distances of the fully autonomous copter with a second copter (left) partially manually controlled and (right) with activated sonars and deactivated rotors.

is controlled autonomously, but the movement in the xy-plane is done manually. As illustrated in Figure 5 (left graph), the fully autonomous copter is very stable. We additionally measured the sensory data as shown in Figure 6 (left graph) and observe that even though the sensor values are very noisy, the copter is relatively stable. The noise of the sonar data is partially created by the ”walls” which are out of foils and move once a copter is in their vicinity. Consequently, even if both copters are close to each other, the airflow generated by them has a much stronger impact on the walls than on the copters themselves.

Experiment 4: The goal of the fourth experiment is to evaluate the interaction between the distance sensors. To this end, we let one copter fly fully autonomously in the arena and added the second copter without letting it fly. Afterwards we rotate the non-flying copter slowly around its z-axis. On specific positions, we observe heavy disturbances in the sensory data of the fully autonomous copter shown in Figure 6 (right graph) leading to unstable behaviour. Th graph shows heavy disturbances in the sonar data. Unfortunately, these disturbances occurred periodically, which induce an oscillation in the copter, leading to a crash with a non-traceable speed by the tracking system. Therefore, we strongly believe that the inability to create a stable multi-copter swarm behaviour in the real scenario is the result of crosstalk between the sensors of the copters. In order to extend the existing sensor model of the simulation, we evaluate the effect of the crosstalk between sensors in a static scenario. The result can be observed in Figure 7. The left figure shows the behaviour of a copter detecting the walls of the arena, while the copter is being rotated 360 degrees. It can be observed that the sum of opposite sensors never stays approximately the same. The right figure shows the same

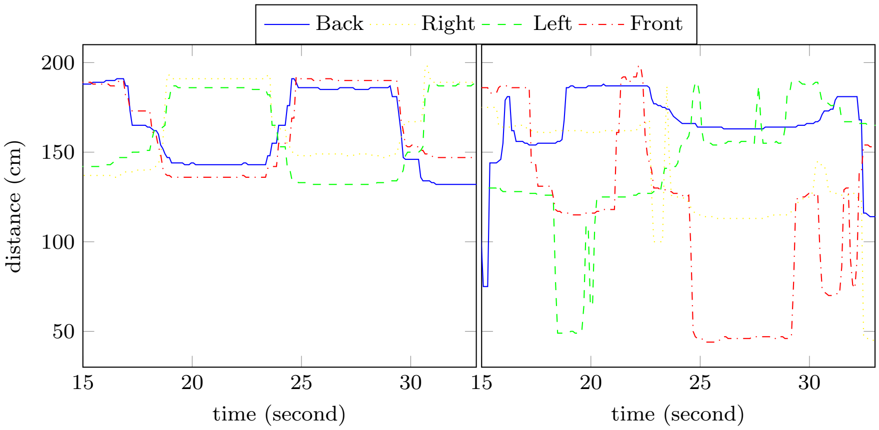


Fig. 7: Evaluation of a single copter's sonars in the arena. The copter is slowly rotated in 360 degrees with deactivated rotors (left). Right: Same as left but with a second copter additionally placed in the arena with deactivated rotors.

behaviour, but with the presence of a second copter with activated sonar sensors in the arena. In this figure some large and long-term disturbances are visible indicating strong interference between the copters.

The above experiments offer more research for swarm behaviour of quadcopters in indoor (small) arena, since the observed long term disturbance of the sonar values instead of the expected short interferences are very hard to handle using sensor signal processing. One possible explanation is the fixed measurement frequency of the sonars, which together with the good clocks of the copters, couple the sonars of the copters. In order to mitigate the problem, we can use a randomized measurement frequency of the sonars and use sophisticated filter schemes such as Kalman-filters to filter the short interferences.

The second important result is the observation that a larger swarm needs a significantly larger arena to be evaluated. This is mainly caused by the slow sensors and the corresponding errors, which forces the copters to occasionally "misbehave". Therefore, the security area established by the repulsion cannot be chosen to be small and a larger arena is definitely necessary.

5 Conclusion and Future work

In this paper we propose a new platform for testing swarms of quadcopters in both simulation and real-world. The major contribution of the platform is a stable autonomous behaviour of indoor micro quadcopters without using any external positioning systems in an augmented arena enabling reproducable experiments. We present a model for such copters in real-world and simulation and analyse the performance using a swarm behaviour. While the experiments in simulation deliver a very good performance of the copters, we observe that the real-world tests encounter more difficulties. Hence one of the major findings of this paper is that the simulation cannot replace real-world tests especially in the swarm robotic context. Nevertheless simulations are necessary tools to develop new algorithms and perform off-line tests. Furthermore, it seems that the interactions of copters with each other and the environment have a large impact on the behaviours and require more research to model them in simulation. In future, we intend to add more sensors such as PX4-Optical Flow and wireless distance sensors to the copters to mitigate the susceptibility of the sonar sensors. Additionally, we aim to optimize the simulation framework to include real-time values and incorporate virtual and dynamic landscapes to the real and virtual arena.

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