Tampere University of Applied Sciences

Particulate Matter Measurement Using Unmanned Aerial Vehicle

Developing of Inlet Systems

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ABSTRACT

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Particulate Matter Measurement Using Unmanned Aerial Vehicle
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This thesis was commissioned by Tampere University of Applied Sciences. Research related to application of Unmanned Aerial Vehicles had been conducted by the Department of Physics in TAMK and students of Energy and Environmental Engineering degree program in previous years. Providing opportunities for academical research in the area.

The aim of the thesis is to determine optimal inlet system for the particulate matter measurement sensor that is simultaneously suitable for installation on the body of an Unmanned Aerial Vehicle, in case of this study drone DJI Phantom 4 Pro.

Particulate matter concentration behavior was studied in the first experiment of pollution mapping in Physics Laboratory at TAMK. Using data of PM2.5 and PM10 mass concentrations extracted from Trotec PC220 and DustTrak air quality sensors, color grip maps were produced. They indicated the rate at which particulate matter was settling. Relationship of the results from two sensors was determined. It was then used to correct PM10 concentration data extracted by Trotec in order to analyze results comprehensively. The second part of the experiment involved test flights of the drone with cone inlet system and ‘stack of plates’ system attached to it at 15 and 40 centimeters above the drone.

According to the results, it takes PM10 8 minutes to settle below the value of 100 $\mu g/m^3$ and 11 minutes for PM2.5 to settle below 50 $\mu g/m^3$. The set-up that performed the best was the ‘stack of plate’ system at 15 cm, while the funnel shape of the cone system seemed to have collected twice as much particles. Weight limitation for Phantom 4 Pro was found at 680 grams, at which point the set-up and the drone started produce oscillations with an amplitude of approximately 20 centimeters.

Further studies on the subject under different conditions and particle contamination systems are needed to find more about correlation between types of inlet systems and their performance in practical applications.

Key words: particulate matter, UAV application, air emission, inlet systems.

CONTENTS

ABBREVIATIONS AND TERMS

3D	3 dimensional
$CaCO_3$	Calcium Carbonate
NAAQSs	National Ambient Air Quality Standards
PAH	Polyaromatic Hydrocarbons
PM	Particulate matter
TAMK	Tampere University of Applied Sciences
UAV	Unmanned Aerial Vehicle
WHO	World Health Organization

1 INTRODUCTION

Particulate Matter (PM) is a term that refers to disperse airborne solid and liquid particles with varying size and form. PM of varying sizes have different settlement rate: some particles can settle within seconds; others might take a couple of weeks (Wark 1998). WHO (World Health Organization) has projected that particle pollution in the air serves as a reason of occurrence of 1% of lung diseases and 3% of lower airways and lungs. In EU alone, it results in almost 300,000 early death yearly. (Fenger 2009)

Particles are capable of carrying hydrophobic highly toxic substances. Those include PAH, dioxins and heavy metals. Particles are considered to be toxic because they can irritate and damage cell lining of the respiratory system. The depth of the penetration inside the lungs and the degree of the damage depends on the size of the particles and concentration of them in the air. Particles are perceived as health hazard of air emissions for acute illnesses and chronic diseases. (Fenger 2009)

PM Regulations. National Ambient Air Qualitys Standards have classified such substances as CO, sulfur oxides, O_3, Lead, NO_2 and particulate matter with diameters of 10 and 2.5 μm, PM10 and PM2.5 respectively as potentially harming for human health under prolonged exposure in ambient air. (Godish 2004)

In most cases of air quality measurements, particulate matter of the size less than 10 and 2,5 μm are measured, as those groups have the most effect on humans (Fenger 2009). PM2.5 & PM10. PM10 consists of particles with the diameter close to the size of 10 μm. Likewise PM2.5 – 2.5 μm (Godish 2004). In ambient air particles usually take place in three size groups: termed (0.01-0.1 μm), fine (0.1-2.5 μm) and coarse (<2.5 μm). Particle mass concentration is significantly influenced by ultrafine particles >0.1 μm which appear to be present in traffic exhaust (Harrison & Hester 2009). Particles present in indoor environment could be attributed to soil, water composition, cooking, combustion appliances, building materials, furnishings etc. (Pluschke 2004)

Application of drones in various industries and for different purposes is getting more and more popular each year, as drone technology develops further. Which makes it more accessible, user-friendly and autonomous. One research regarding development and implementation of the UAV in air quality management was conducted in 2015 by team of researches from The University of Queensland. According to the study, integration of data collected from air quality sensor and autopilot data is possible and can help to define particles in time and space (Alvarado 2015). Another study of the same team year late in 2016, investigated integration of air quality sensors on board of an UAV and the effect of its positioning, weight and wind conditions on collected measurements.

2 AIMS AND METHODS

2.1 Research Question

This research tries to answer the following question: How the type of the inlet system attached to the UAV will influence the results of detection of particulate matter concentration in the air under indoor conditions?

2.2 Aims

Main aim of the work is to determine optimal inlet system for the particulate measurement sensor that is simultaneously suitable for installation on the body of an Unmanned Aerial Vehicle, in this case drone DJI Phantom 4 Pro.

2.3 Methods

The research methods used for the thesis were literature review, experimental work and data analysis. Background theory was collected through academic literature review, during which, such tools as Finna library, Google Scolar and theseus.fi were accessed. In addition, TAMK and Tampere University libraries were visited in search of reliable sources.

Experimental procedure carried out was focused on collecting mass concentration data from two sensors for further analysis and determination of optimal inlet system. During the experiment two particulate matter sensors Trotec PC220 and DustTrak were utilized alongside with spray pump system, that was used for particle distribution on the location, and a drone DJI Phantom 4 Pro, that carried overall system. Once the experimental procedure was completed and all sought numerical data was extracted from the devices, analytical stage of the research began. By comparing data extracted from two sensors for each measurement and interpreting the comparison in graphical form, conclusions regarding the results could be drawn.

3 EQUIPMENT

Experiment consisted of two part following different procedures: pollution mapping and testing of inlet systems. In both cases, DustTrak and Trotec PC220 particulate matter sensors are used for the analysis of air quality via assessing PM2.5 and PM10 concentrations. Aeration of particulate matter solution with the help of air compressor and an air brush took place in both experiments.

Specific inlet systems, cone and plate, have been developed for the purposes of this work, as well as supporting structures to install those systems at two selected heights. Additionally, plenty of connection materials was utilized in attaching set-up to the drone: zip-ties, duct tape and various types of glue.

The drone Phantom 4 Pro DJI played a crucial part in the fulfilment of the experiment. Initially, there have been administrative issues regarding availability of the drone pilot, which put at risk the research overall. Luckily, the incident was solved, and experiment was conducted successfully.

3.1 Inlet Systems

The sensor that was used in this work is mostly unaffected by increased air flow and is capable of sampling in harsh conditions. In order to adapt the drone-sensor apparatus for increased air flow created by propellers, an idea of an inlet system has been explored. The main objective of that system had to be limitation of the influence of air flow on particulate matter count that is being registered by the sensor.

Additionally, the placement of such system required the knowledge regarding the drone in use, such as carrying capacity, air flow patterns created by propellers, physical parameters allowing the system to be mounted on its body etc. Through physical examination of the drone and recommendations from previous experiments conducted by Netra Gnawali in 2018, decision to attach the inlet system above the drone has been reached. In Gnawali's research the sensor and the inlet were mounted on a drone so that the results were compromised by high

velocity air flow created by propellers. Primary reason for extending the inlet upwards being earlier observed relatively low influence and distortion area in the air above the drone while it is operating.

Prototypes of those systems were chosen to be open upwards facing funnel and so called "stack of plates". In earlier stages of development, a third system was also planned to be tested. Similar to the open upwards facing funnel, it was the similar concept in the base with a small addition of the perforated lid. Unfortunately, due to the fact that behaviour of air flow could not be predicted and for the lack of supporting material and data, the concept was not explored.

3.1.1 Open funnel system

The most important factor that needed to be considered during the development if cone funnel inlet system (picture 1) was the material that the set-up would be made from. At first, set-up’s frame was built out of a wooden 60 cm plant support, ordinary plastic kitchen funnel and superglue. Because plastic created a magnetic field that interferes with particulate behaviour, aluminium tape was used to minimize it. The tape covered the upper part of the set-up tightly, with as little disruptions in the surface as possible.

PICTURE 1 Cone inlet system before coverage with aluminum foil.

Another aspect that had to be considered was the weight of the system, since carrying capacity of the drone is limited. The priority was to make the set-up light. Altogether cone funnel system weighted 597 grams at 15 cm and 683 grams at 40 cm.

During the experiment 60cm support was shortened to fit the length of, first, 40 cm and then 15cm. Additional supports and other needed part of the set-up were accessible on site of the experiment, providing back-up.

3.1.2 "Stack of plates" system

PICTURE 2 On the left: middle and bottom plate with connection details installed before aluminum tape coverage. On the right: stack of plate system covered in aluminum tape installed 15 cm above the drone before take off.

This inlet system has been inspired by Alvarado and his team from the University of Queensland, where a similar system has been used for the inlet of the sensor mounted to the UAV. In productions of this system, pot plates for plants made from recycled plastic were used as the main element. Two perforations were made in the bottom plate: one for the support beam and the other for the attachment of the inlet tube (picture 2, left). Major part of the middle plate was removed, in order to provide enough sampling volume for the sensor inlet, but at the same time shelter it from the air flow created by propellers of the drone. Top plate was not modified. Connection between the plates was provided with little support beams situated along the inner radius of each plate. Dimensions of plates are 12,5 cm in outer diameter, 10,5 cm in inner diameter and the height of each individual plate is 2 cm. The height of the system without support bar and connections to the drone is 5 cm.

The set-up was easily attached to the drone trough the same scheme as cone set-up: a support bar fit firmly to the perforation, which allowed for the time savings when it comes to changing set-ups. Overall weight of the system with sensor, tube and all connecting elements was 625 grams at 15 cm when installed above the drone. The weight of the set-up was not measured with supports for 40 cm, since that flight was not performed.

3.2 Sensors: Trotec 220PC & DustTrak

PICTURE 3 Particulate matter sensor Trotec PC220 on the left and TSI DustTrak Aerosol Monitor Model 8520. (Tran 2019)

For the purposes of this research, Trotec PC220 (Picture 3, left) was used as compact sensor to detect particulate matter while attached to a flying drone. Trotec PC220 is a device that counts particles in the air and distributes them by size using light scattering technology. Additionally, this sensor is capable of measuring carbon monoxide and formaldehyde concentrations in limited space. Three methods of particle analysis can be conducted by Trotec: cumulative, differential, concentration. Moreover, device carries out simultaneous measurement of temperature, humidity and dew point. As well as, provides a possibility to document the procedure on the spot using build-in camera. Device can detect particles with size range from 0,3µm to 10µm and calculate number concentration of 6 particle

sizes simultaneously. Whereas for mass concentration, Trotec is capable of extracting data for PM2.5 and PM10 at the same time. While the manual clearly states that Trotec PC220 has function of transferring data from the device to a computer via USB, it appeared to not be working. Therefore, all measurements were extracted by hand from the device. (Trotec 2018)

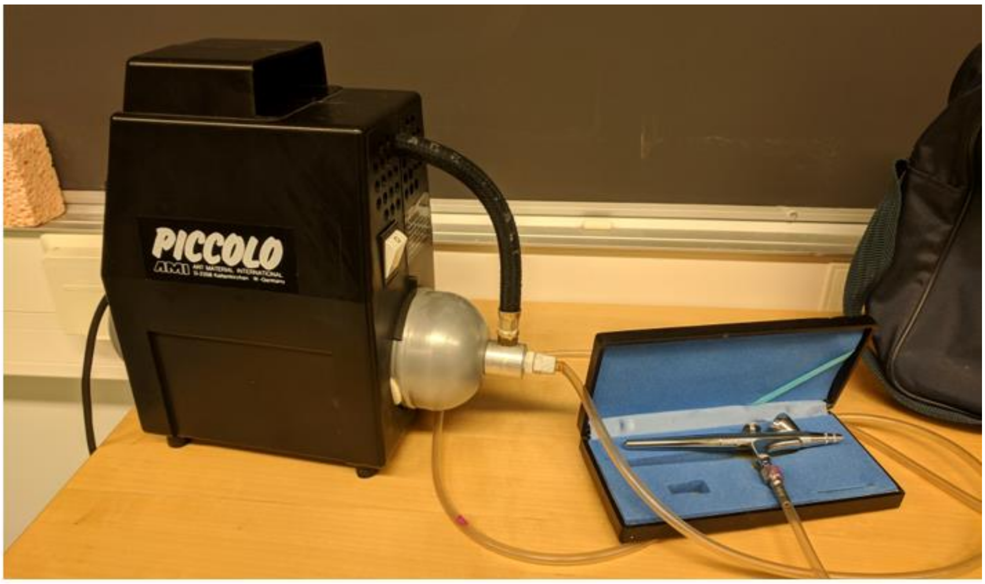
DustTrak Aerosol Monitor (Picture 3, right) was used as a reference sensor to the Trotec PC220 during the experiments. This monitor is applicable for measurements taking place in both indoor and outdoor environments. The working principle is the same as Trotec: 90°C light scattering. The device is capable of measuring particle concentrations for PM10, PM2.5 and PM1.0. The range of the device is calibrated according to ISO 12103-1, A1 test dust. The weight of the device is 1,5 lg, which is far to heavy for even considering it to be mounted on to a drone. (TSI Incorporated 2002)

3.3 Drone Phantom 4 Pro DJI

Out of all the drones that were available at tamk, this particluar one (picture 4) was chosen because of it’s reliability in controlling and visionposition system. Since the expereiment was conducted indoors, visionposition system was usefull with avoiding obsticles and lowered the safety risks for the participants. Additionaly, the drone provided optimal surface area on the top cover for the attachment of the support structure for the inlet systems and the stands of the drone were suitable for positioning Trotec underneath them. Even thought the GPS system module is positioned directly underneath the top cover, the fact that the experiment took place in limited space made it unnessessery and allowed to cover the surface.

PICTURE 4 UAV - Drone Phantom 4 Pro DJI. (DJI)

3.4 Pump and Particulate Matter Solution



PICTURE 5 Air Compressor and a spray-paint brush connected to it.

Air compressor and a spray-paint brash (picture 5) were used to create artificial pollution of the location with a solution containing particulate matter. Since the number of particles in the room under standard conditions is not enough to provide a base for a comprehensive study. Taking into account the presence of the drone and the airflow created by propellers, additional particulate matter is necessary. The solution was prepared from clay powder, calcium carbonate ($CaCO_3$) and water, 2 grams of both clay and $CaCO_3$ and 200ml of water.

4 EXPERIMENT

Conditions of both experiments conducted for the purposes of this research were similar: contamination of the location with particulate matter was artificial. In the case of pollution mapping solution of clay and calcium carbonate was sprayed beforehand in one time period and then the measurements were taken. However, during the testing of inlet systems, aeration was continuous in between time period of 10 minutes. Both experiments were preformed in one location with dimensions of 7 by 8 meters.

Both experiments involved working while particulate matter was present in the air, which poses a health hazard to participants. For protection of respiratory system, it was mandatory to wear protection masks all through experiments. Additionally, with insistence of a pilot, helmets and goggles were worn as a precaution while the drone was in flying mode.

4.1 Pollution mapping

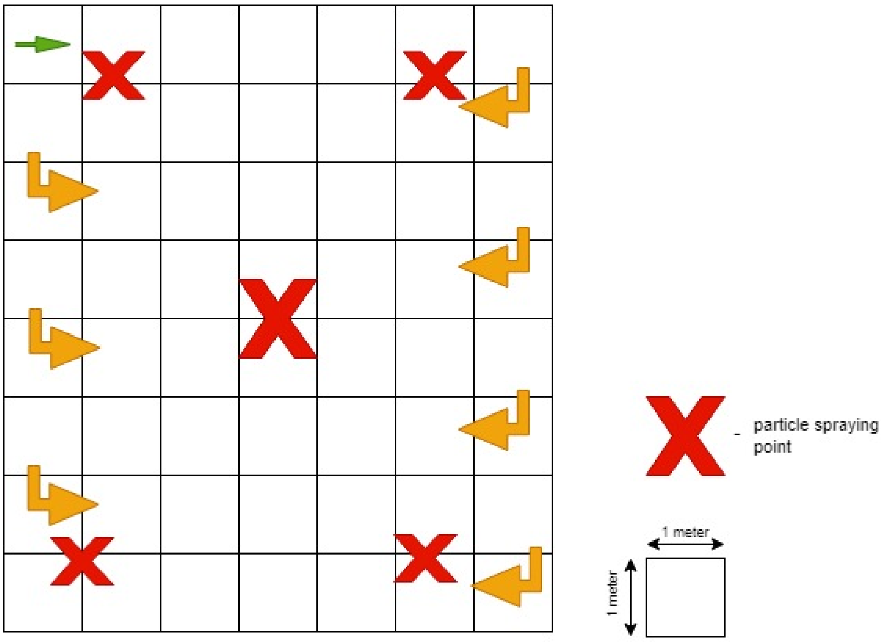
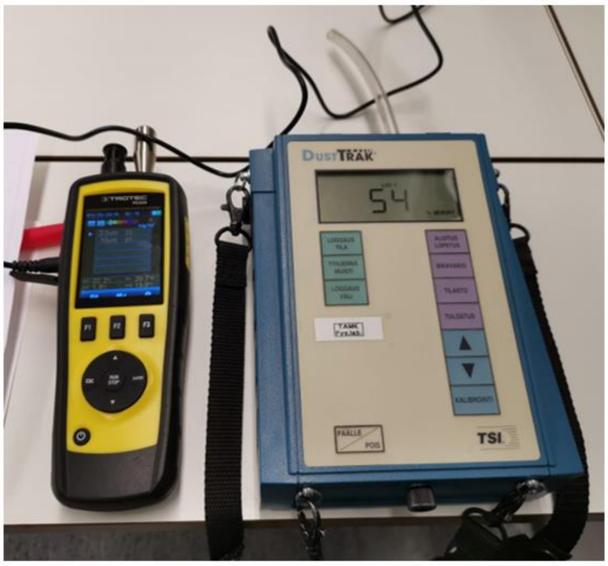


FIGURE 1 Schematic representation of pollution mapping experiment. 7 by 8 meters grid map of the location, particle spraying points, sequence in which measurements were taken.

Pollution mapping was conducted in order to study applicability of the spray-paint brush and determine the aproxiamte settling rate of the particles inside laboratory where drone will be operated. Said laboratory is located in E2-13, second floor of the E building of Tampere University of Applied Sciences Kauppi campus.

The laboratory was divided in to 56 even squares with the area of 1 m^2. As can be seen on Figure 1, measurements had started from the top left corner of the room and proceeded to be taken as indicated by arows up until the bottom left corner. Red X marks represent the point where solution containing particulate matter had been sprayed with spray paint prush and an air compressor once in every corner and twice in the middle of the room. Each full spray contained 1.8 ml of the solution. All artificial particle contamination had been done 10 minutes pripor to the start of the measurment.



PICTURE 6 Position of Trotec PC220 and DustTrak sensors during pollution mapping measurements. (Tran 2019)

Afterwards, measurements started to take place. Picture 6 illustrates relative positioning of Trotec PC220 and DustTrak. Both of the devices are situated 1 meter above the ground level at every measurement point and were taken simultaniously. Overall process took 30 minutes. Each measurment recorded was an average value from the measurements collected for 15 seconds. To perform a comprehensive analysis of the results, concetrations of particles In the air has also been taken before contamination of the area and one hour after.

4.2 Testing of inlet systems

Air flow patterns created by an average drone hovering in space have been studied by Alvarado, Cliff, Erskine, Gonzalez & Heuff (2017) from the university of Queensland. The 3D model displayed below indicates how the areas around the drone are affected by the wind speed. From Figure 2, one can make an observation that the area least exposed to the airflow of the propellers and simultaneously the closest to the body of the drone is directly above it. Research of An Tran (2019) was focused on determining the height above the drone that is most suitable for conducting measurements at. In accordance with her findings, heights of 15 cm and 40 cm above the drone were chosen to be investigated further in this work.

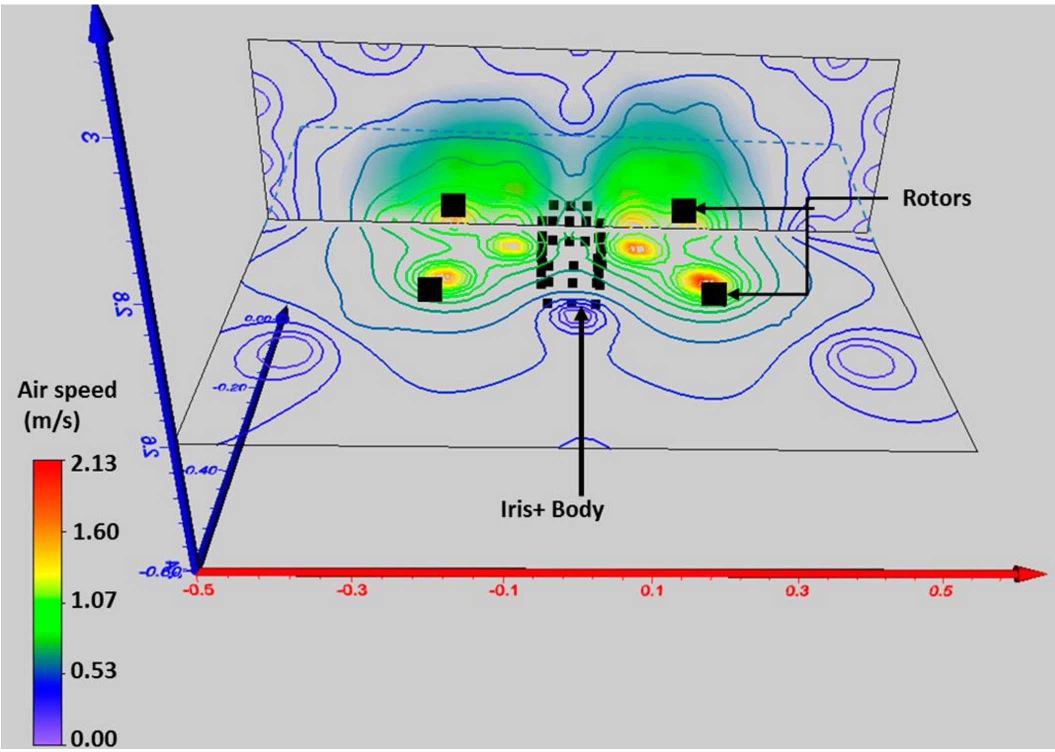


FIGURE 2 3D visualization model of the airflow created by propellers of the drone. (Alvarado, Cliff, Erskile, Gonzalez & Heuff 2017)

The area was artificially contaminated using spray-paint airbrush and the solution containing undissolved particulate matter. During preparation stage, the solution had been sprayed from 4 corners twice and for the duration of the experiment overall, from the center every 10 minutes. According the results of pollution map-

ping experiment, time increments of 10 minutes were enough to maintain relevantly steady level of particle concentration in the area. Flights were scheduled to take place 2-3 minutes after aeration.

Before the experiment started, background measurement with the Trotec PC220 was taken. The schematic representation of the experiment could be seen on figure 3. The set-up that consists of the inlet system, Trotec PC220 sensor and the tube connecting those two, mounted on the drone is the central shape on the figure. DustTrak, that is used as a reference device in this experiment, is mounted on the height of 165 cm above the floor, 2 meters away from the drone. Red X marks the spot from which every 10 minutes spraying takes place.

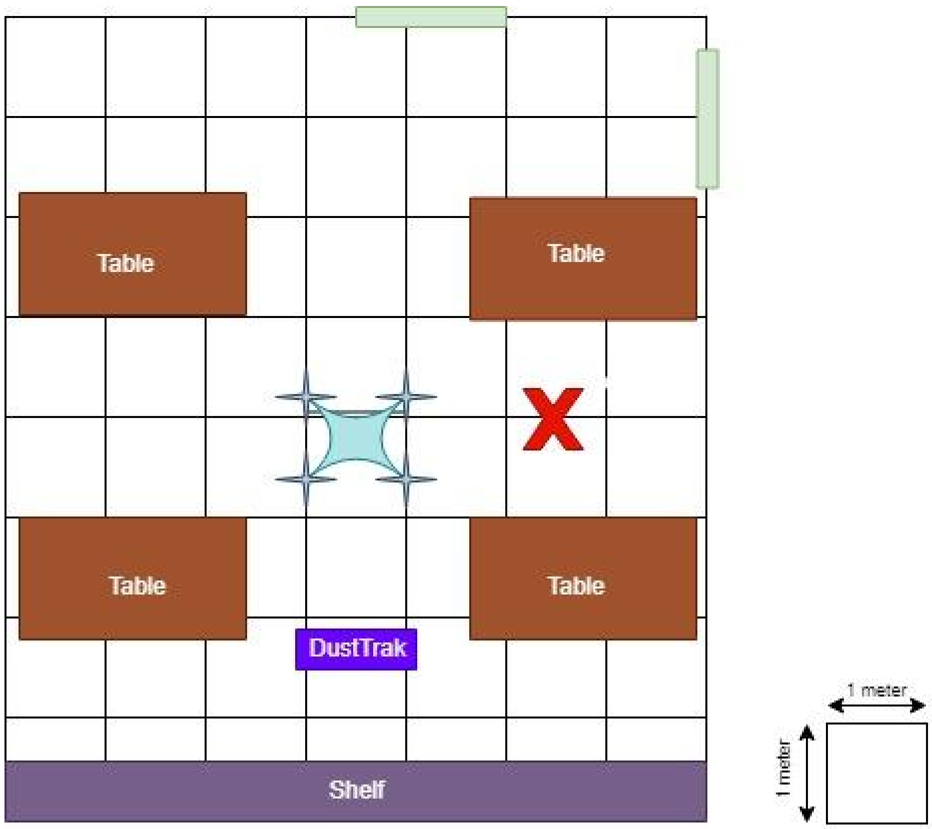
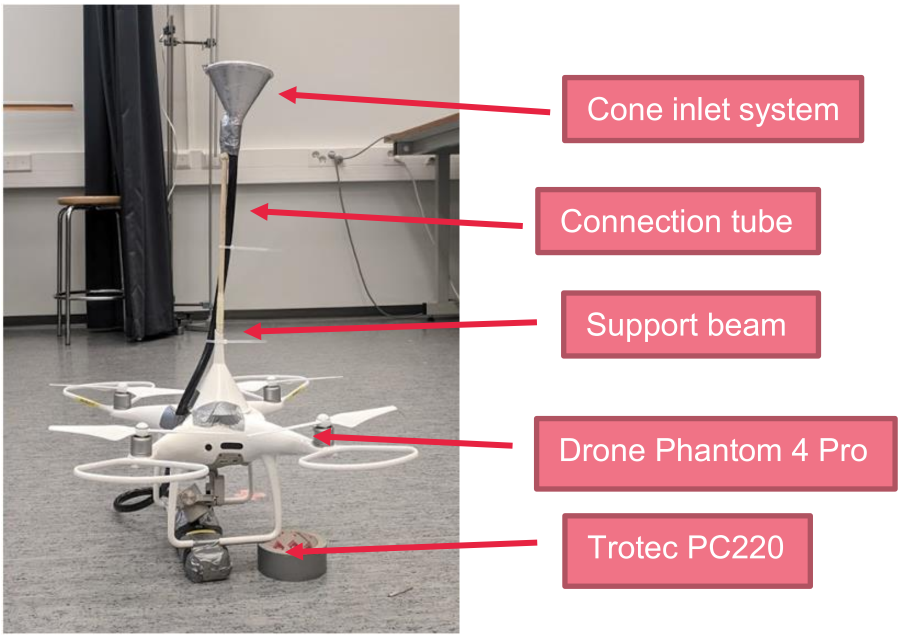


FIGURE 3 Schematic representation of experiment's logistics. X marks the spot from which contamination was made, shape in the center - drone with inlet set-up mounted. Green rectangles on the top of the picture represent entrances to the room.

First flight was performed without any inlet system mounted on the drone. Instead the inlet has been extended up to 15 cm above the drone, but it was left exposed

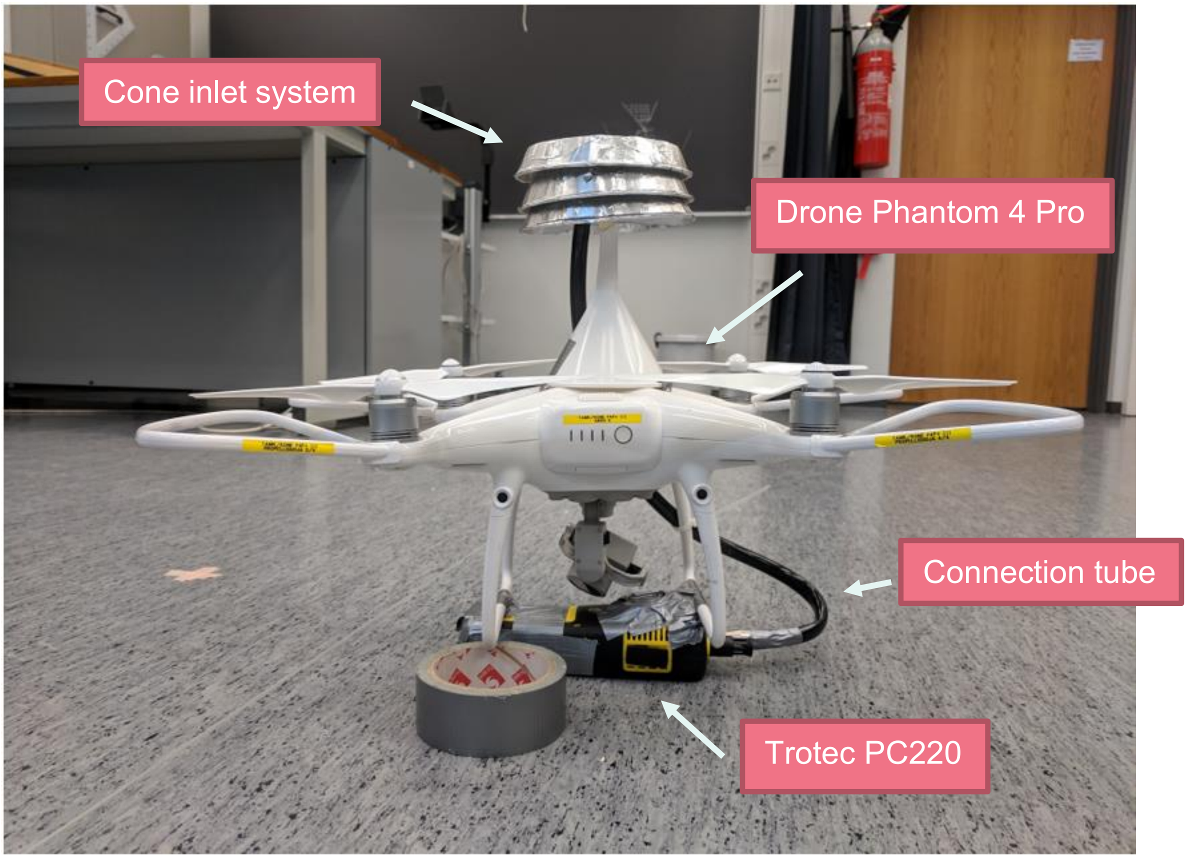
and without any additional modifications. After that 40 cm height was tested, without any set-ups attached as well. Next flight was supposed to be one with cone set-up on 40 cm above the drone, picture 7. Unfortunately, while flighting, drone started to oscillate under the weight of the system. Pilot had tried his best to maintain a stable flight conditions, but, sadly, the experiment has ended. During the failed flight Trotec PC220 was continuously collecting measurements that are later discussed in section 6 Results. As the plate system weights more than cone funnel one, it was decided on the spot, and opinion of the pilot was the same, to not mount it on 40 cm and abandon the plan of that flight, in order not to damage the equipment and minimize the health hazard that is caused by oscillation of the drone. Instead, both systems then were mounted at 15 cm each and tested separately. Plate system connected on to the drone, the set up directly before the flight can be seen on picture 8.



PICTURE 7 Cone inlet set-up attached to the drone at 40 cm above it.

Trotec PC220 was preprogrammed to collect measurements in cycles of 20 seconds with breaks of 10 seconds. As each flight lasted for approximately 2 minutes, it was enough to collect at least 3 samples. Simultaneously, values calculated by DustTrak were recorded by hand.

The complexity of the set-up installed on the drone limited the landing possibilities for the pilot, so he was forced to perform hand-landing everytime in order not to damage Trotec PC220 that was attched underneath the stands of the drone.



PICTURE 8 Plate inlet set-up attached to the drone at the height of 15 cm above it.

5 RESULTS

5.1 Pollution mapping

Before taking measurements, solution containing particulate matter had been sprayed in each corner of the room once and twice in the centre. All together approximately 11 ml of the solution had been sprayed from the height of 2 meters. The area of the laboratory where experiment was carried out was 56 m^2, which made up 56 squares for investigation on the level of particulate matter concentration. Extracted values were analysed in MS Excel and compiled into 3 figures. Figure 4 represents PM10 concentrations measured by Trotec PC220, figure 5 – PM10 concentrations measured by DustTrak, figure 6 – PM2.5 concentrations measured by Trotec PC220. Overall, measurements took approximately 30 minutes. Additional background values were taken before spraying the solution and half an hour after the experiment. Results indicated that particles completely settled in one hour, since the concentration of particulate matter was varying from 2 to 3 µg/m^3 in both cases

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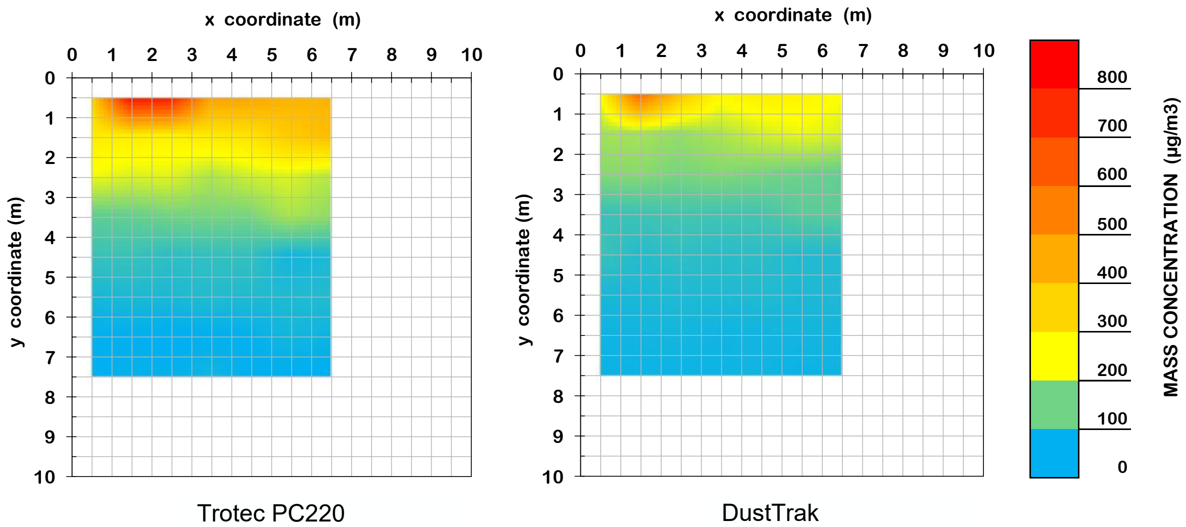


FIGURE 4 Color grid map of PM10 concentrations (in µg/m^3) measured by Trotec PC220 on the left & by DustTrak on the right. (Tran 2019)

Comparison of the results gathered by Trotec PC220 and DustTrak during pollution mapping experiment for PM10 concentration can be seen from figure 4. Peculiarity that stands out the most is different shade of 2 color grid maps under the

same applied scale for concentration values. Which indicates that overall measurements collected by DustTrak are lower than those of Trotec. This could be observed through comparison of left top corners of both maps. Trotec has detected PM10 concentration of 775 μg/m³, while DustTrak only 574 μg/m³. As the sampling progressed along the grid, with directions schematically indicated in figure 3, concentration decreased, resulting in a gradient. For Trotec PC220 color grid map of PM10 concentration change of the gradient, and with it change of the concentration from red (800 μg/m³) to green (100 μg/m³) happens rather rapidly up until 4-meter mark on the y-axis. This change takes up approximately half of the grid, which means that it takes approximately 15 minutes for particles to settle to the point when concentration decreases by a factor of 4. Below 4-meter mark preliminary color on the grid is evenly distributed blue. This indicates that after concentration decreases to below 100 μg/m³, overall speed of particle settlement slows down. The same trend could be observed from DustTrak color grip map.

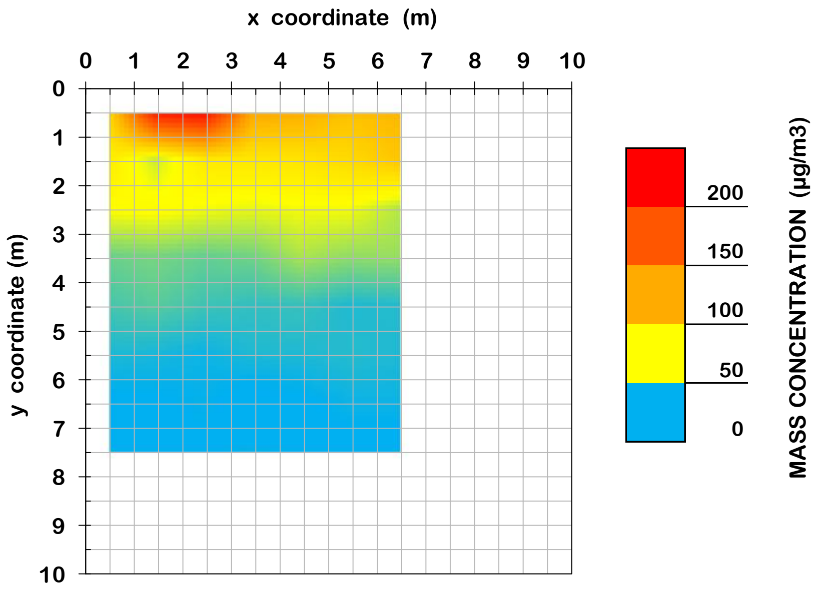


FIGURE 5 Color grid map of PM2.5 concentrations measured by Trotec PC220, in μg/m³. (Tran 2019)

Similarly, the trend observed in figure 4, behavior of the PM2.5 can be observed in figure 5. The top left corner of the map here is also marked as having the highest concentration, 190 μg/m³. More than half of the map is colored blue, which indicates concentrations of less than 50 μg/m³.

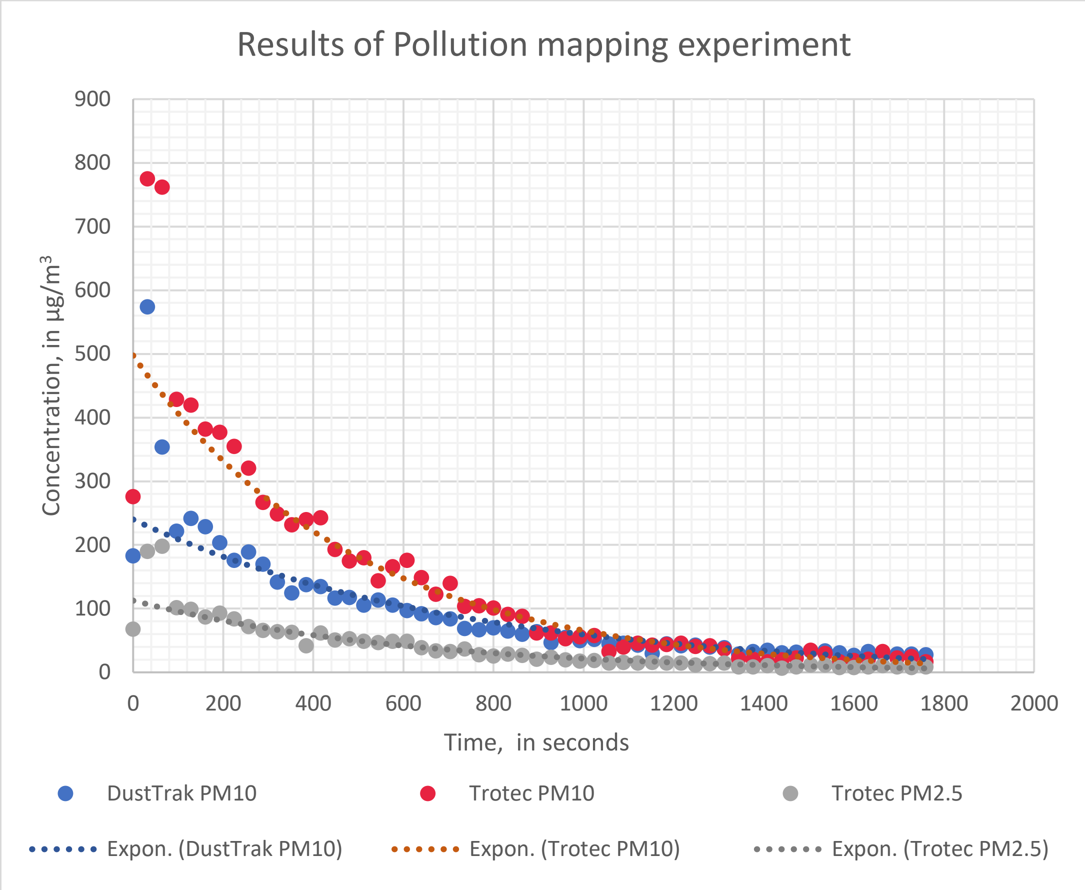


FIGURE 6 Dependence of Trotec PC220 PM2.5 and PM10 mass concentrations & DustTrak PM10 concentrations over the time of the experiment. Exponential trendllines are present on the figure.

Figure 6 represents the change of concentrations of PM10 and PM2.5 through time. One can clearly see a common trend between sets of values: overall decrease. The biggest slope of the trendline is with Trotec PC220 at PM10, which indicates faster settlement of the particles. Interestingly, DustTrak has less steep slope, while measurements were taken simultaneously, at the same height (picture 6). The settlement rate of PM2.5 taken by Trotec is much slower than those of PM10 measurements.

Throughout the experiment values collected by DustTrak significantly vary from those collected by Trotec PC220. In order to find correlation and dependence between those values, figure 7 was put together. It represents correlation between PM10 concentrations gathered by DustTrak and Trotec. Graph presented below will be further used for conversion of Trotec's PM10 mass concentration

results to expected DustTrak data using DustTrak-Trotec function: y = 0,5032x + 20,324 with coefficient of determination – 0,981.

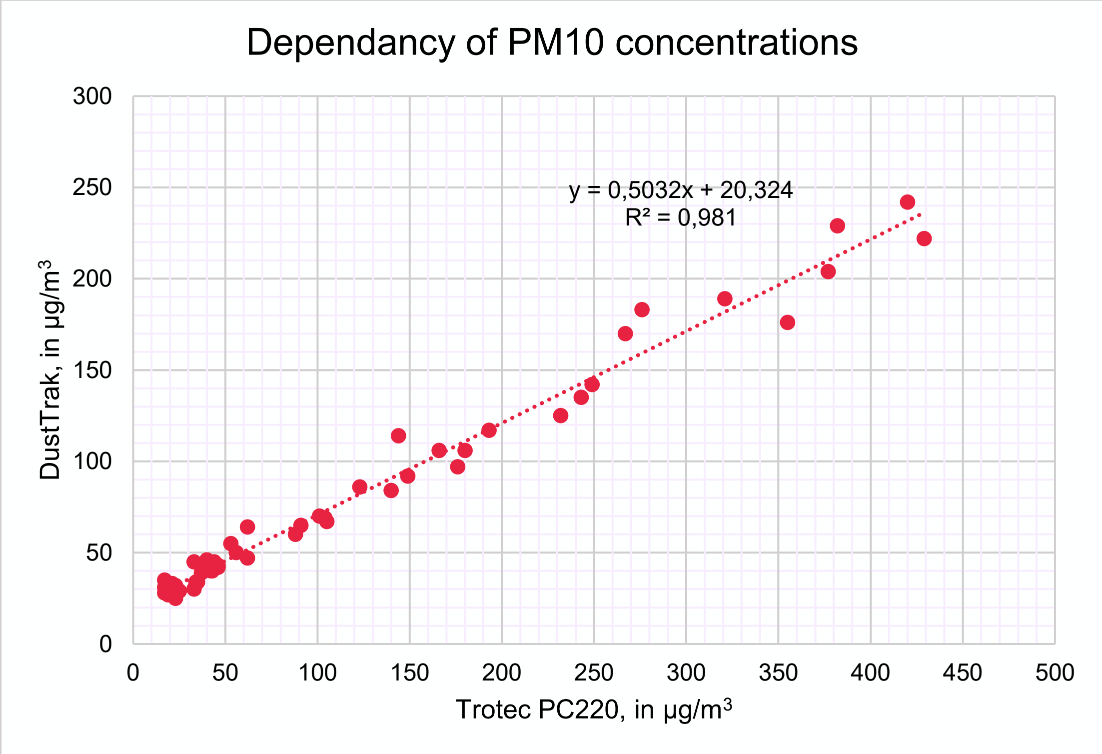


FIGURE 7 Relationship between PM10 concentration values collected by Trotec PC220 and DustTrak (Tran 2019)

5.2 Testing of inlet systems

According to the study conducted by An Tran in 2019, from the range of 10-50 cm above the drone, 2 heights were the most interesting to test with inlet systems. At the height of 15 cm, anemometer detected 2,7 m/s speed of air created by propellers. At the height of 40 cm – 0,9 m/s. Additionally, most optimal correlation between the results of two sensors used for the experiment lies in the increments that corresponds to 40 cm. (Tran 2019)

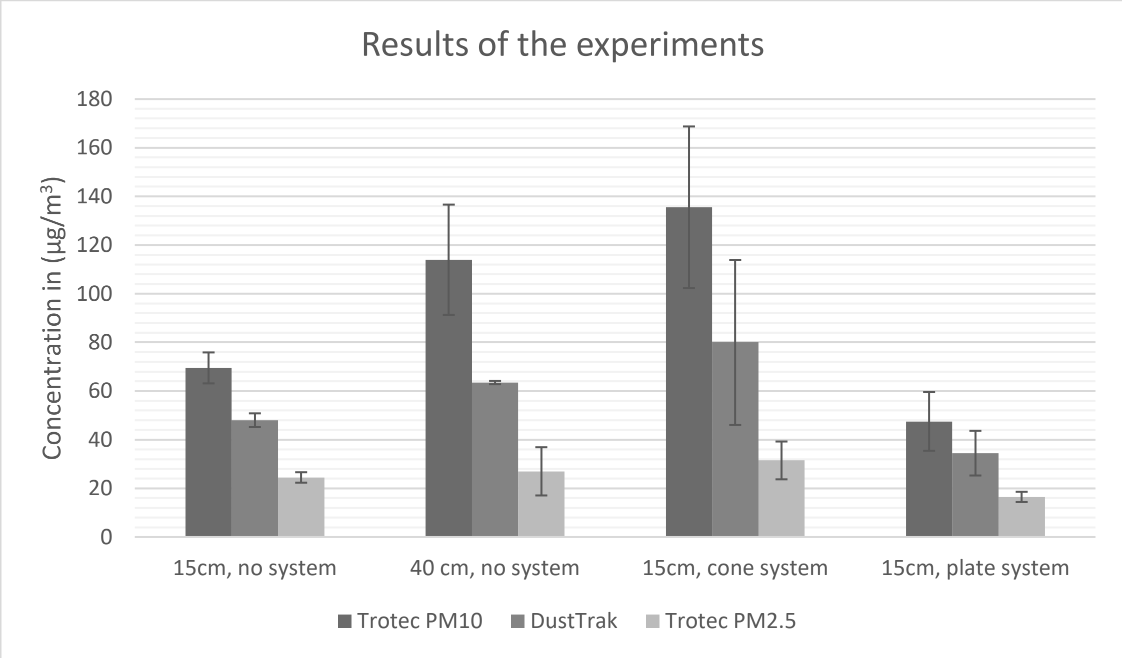


FIGURE 8 Bar chart representing average of measured concentration values (in µg/m^3) detected by DustTrak and Trotec PC220 at PM10 and PM 2.5 during each flight with standard deviation marked.

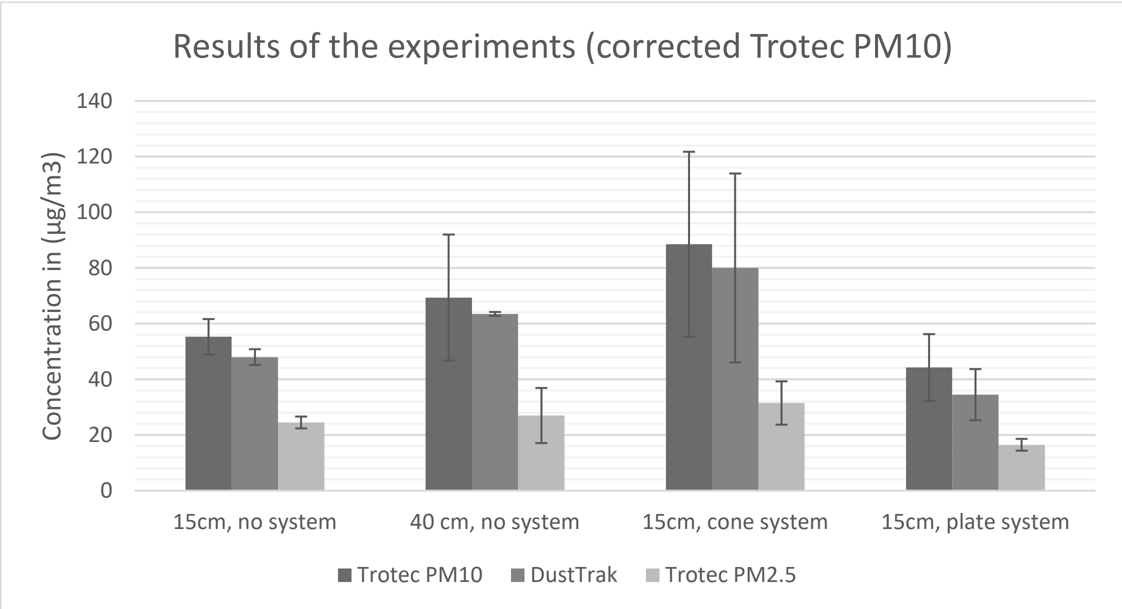


FIGURE 9 Bar chart representing average of measured concentration values (in µg/m3) detected by DustTrak and Trotec PC220 at PM10 (Corrected value) and PM 2.5 during each flight with standard deviation marked.

Horizontal axe represents the nature of conducted experiments. Color code is used for DustTrak device and Trotec PC220 at the diameter of particulate matter that have been gathered during four drone flights. First two flights, at 15 cm and 40cm, have been done without the inlet systems to determine the optimal height

to install the system above the drone so that measurements would be gathered more effectively.

According to Figure 8, the most fluctuated results are of the experiment involving cone system inlet set up 15 cm above the drone. As the standard deviation clearly shows on the figure, measurements of PM10 taken by DustTrak and Trotec PC220 have large window of variation.

On the contrast, most noticeable information on the figure is the similarity of the results in flights with no system and plate system with 15 cm distance between the drone and the set-up. Another peculiarity lays in standard deviation of results from those experiments: in both cases, variation in results taken by DustTrak and Trotec PC220 of PM10 at each instance are similar to each other.

Figure 9 is different to figure 8 only in one thing: that mean value of the mass concentration of PM10 of Trotec PC220 had been corrected according to the equation extracted from figure 7. While all results are still higher than actual DustTrak values, the difference between those values had been adjusted. Most affected by the adjustment are the results of the two flights at 15 cm with cone system and 40 cm with no system.

5.2.1 No system flights at 15 cm and 40 cm

	Sensor	Concentration				S.D.	Error	Mean	Mean (corrected)
Distance of measurement: 15cm	Trotec PM 10, (µg/m^3)	74	67	65	-	6,3640	3,6742	69,5	55,30
	DustTrak, (µg/m^3)	50	55	48	46	2,8284	1,6330	49	-
Distance of measurement: 40cm	Trotec PM 10, (µg/m^3)	130	106	65	-	45,9619	26,5361	97,5	69,386
	DustTrak, (µg/m^3)	64	69	65	63	0,7071	0,4082	64,5	-

TABLE 1 Results from experiments at 15 cm and 40 cm above the drone with no inlet systems attached. Trotec PC220 and Dustrak, concentrations of PM10.

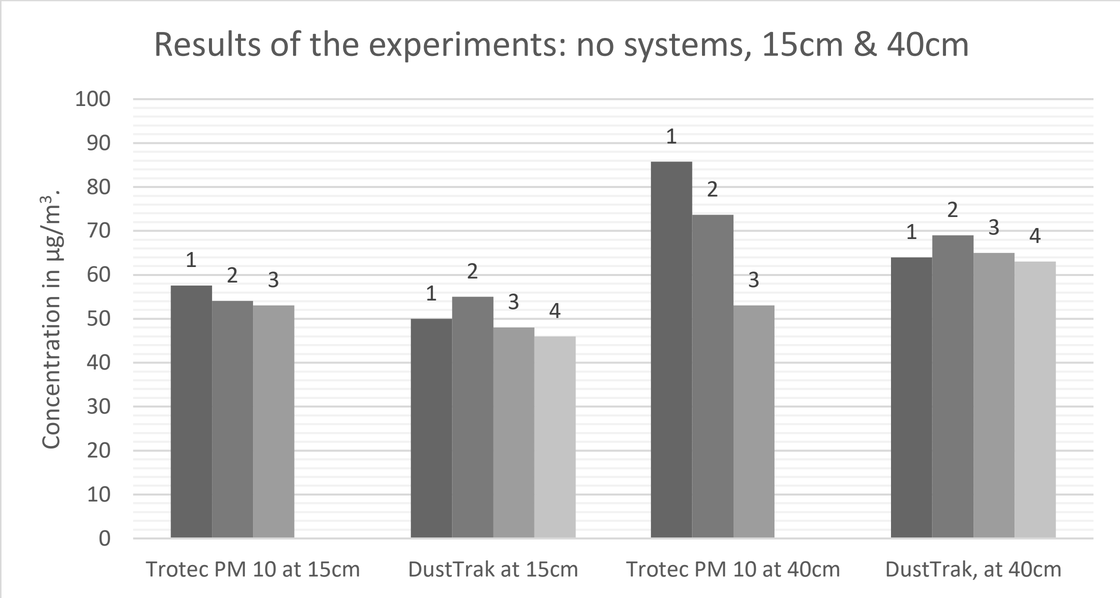


FIGURE 10 Comparison of PM10 concentrations collected by Trotec PC220 (corrected) and DustTrak at 15 and 40 cm above the drone without any systems attached, in µg/m^3. Number on top of bars indicate simultaneousness of the measurements.

From the figure above, it is clear to see the difference in concentrations between Trotec PC220 at 15 and 40cm. The concentration of PM10 at 40 cm measured by Trotec PC220 decreased by a third, in a span of 90 seconds. Most probably this is due to effect of the propellers.

It is worth noting the similarity of DustTrak results, as it was positioned stationary 2 meters away from the drone flight area and on approximately same height. Even though, the concentrations at 40cm measurements are higher than those taken at 15 cm, overall pattern of measurements is the same with the spike during the second and further slight decrease. The spike is likely caused by the motion of the propellers and them directing more particulate matter towards DustTrak after 45 from the start of the flights.

Results of Trotec PM10 displayed on the figure 10 have been corrected by DustTak-Trotec dependence displayed in figure 7: y = 0,5032x + 20,324. In order to adjust results and make the comparison more comprehensible.

.

	Sensor	Concentration			S.D.	Error	Mean
Distance of measurement: 15cm	Trotec PM2.5, (µg/m³)	26	25	23	2,1213	1,2247	24,5
Distance of measurement: 40cm	Trotec PM2.5, (µg/m³)	34	25	20	9,8995	5,7155	27,0

TABLE 2 Results from experiments at 15am and 40cm above the drone with no inlet systems attached. Trotec PC220 concentrations of PM2.5.

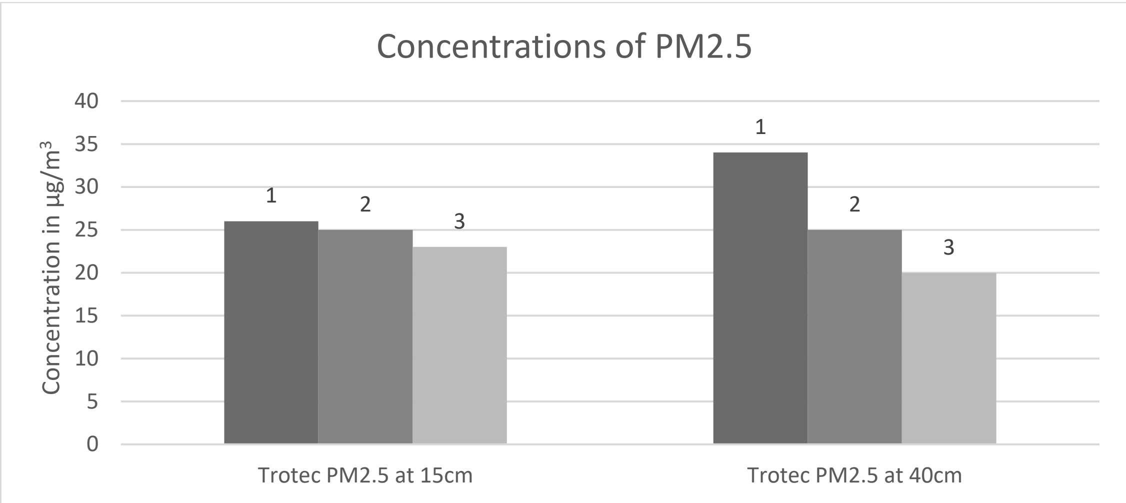


FIGURE 11 Comparison of PM2.5 concentrations collected by Trotec PC220 at 15 and 40 cm above the drone without any systems attached, in µg/m³. Numbers above the bars indicate the order with which measurements were taken.

The results displayed in figure 11, represent PM2.5 values in the case of the experiments at 15cm and 40cm with no systems. Values of the experiment performed at 40 cm are overall higher and differ more noticeably than those of the flight with no system installed at 15 cm.

5.2.2 Cone and Plate inlet systems flights at 15cm

	Sensor	Concentration				S.D.	Error	Mean	Mean (cor.)
Distance of measurement: 15cm / cone inlet system	Trotec PM 10, (µg/m³)	159	120	112	-	33,2340	19,1877	135,5	88,51
	DustTrak, (µg/m³)	104	86	62	56	33,9411	16,9706	83	-

Distance of measurement: 15cm / plate inlet system	Trotec PM 10, (µg/m^3)	56	47	39	-	12,0208	6,9402	47,5	44,27
	DustTrak, (µg/m^3)	41	41	37	28	9,1924	4,5962	39	-

TABLE 3 Results from experiments at 15am above the drone with cone and plate inlet systems attached. Trotec PC220 and DustTrak concentrations of PM10.

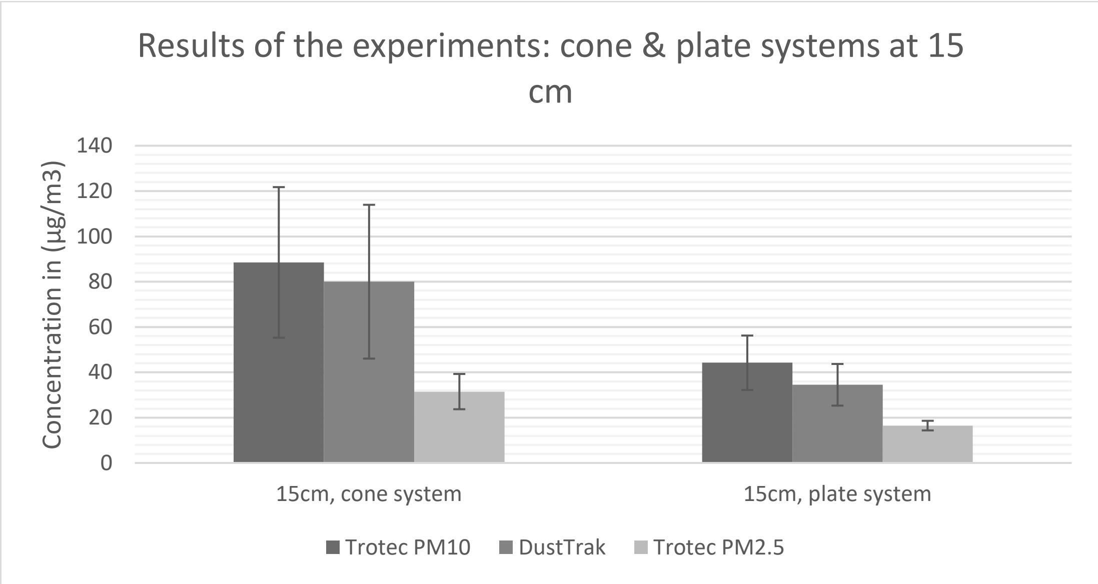


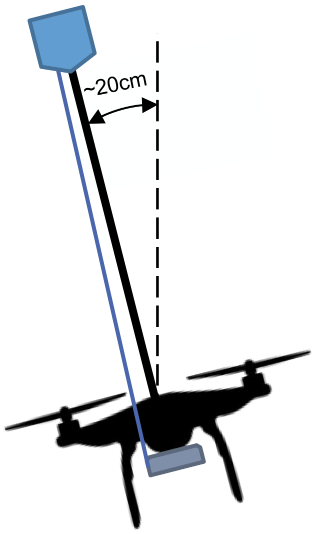
FIGURE 12 Comparison of corrected PM10 concentrations collected by Trotec PC220 and DustTrak at 15 cm above the drone with cone, plate and no systems attached, in µg/m^3.

Generally, values collected during the flight with a cone system installed on the drone at the height of 15 cm above it is twice as much as results of the plate system for every sensor and concentration. Although conditions created artificially are not stable, these results were collected 15 minutes apart with additional spraying of the solution in between. Here the standard deviation of the results from both Trotec PC220 and DustTrak of PM10 stands out as the highest from all presented.

Results of Trotec PM10 displayed on the figure 12 have been corrected by DustTak-Trotec dependence displayed in figure 7: y = 0,5032x + 20,324. In order to adjust results and make the comparison more comprehensible.

5.2.3 No system and failed Cone inlet system flights at 40cm

One of the planed experiments included a flight with a cone inlet system attached at 40cm above the drone. Observed oscillations of the drone with that set-up reached maximum amplitude of 20cm from the vertical access of the drone (picture 8). All together 4 flight have been dedicated to conducting the experiment. Alas, during each flight, drone was oscillating more and more. First flights were no-longer than 10 seconds, as the pilot was afraid to lose the control of the drone and break the drone. By the fourth flight, drone was kept in the air for approximately 30 seconds. While the drone was in the air, Trotec PC220 sensor managed to get some measurements. As the experiment was deemed to be a failure for the account of the mass that was attached to the drone, which exceeded the carrying capacity of the drone, the idea of proceeding with measurements at



PICTURE 9 Model of the oscillation of the drone during the experiment with cone set-up at 40 cm above the drone.

40cm was abandoned. This notion was also backend by the results from the experiment with empty systems. According to the data, distance of 15 cm from the drone is less affected by the air flow during the flight than 40cm. The mass of the system added up to 683 grams.

Nevertheless, the data extracted from Trotec PC220 from that experiment is used in this work to be compared and analyzed, first, with a no system set-up results and then with the cone inlet system at 15cm above the drone.

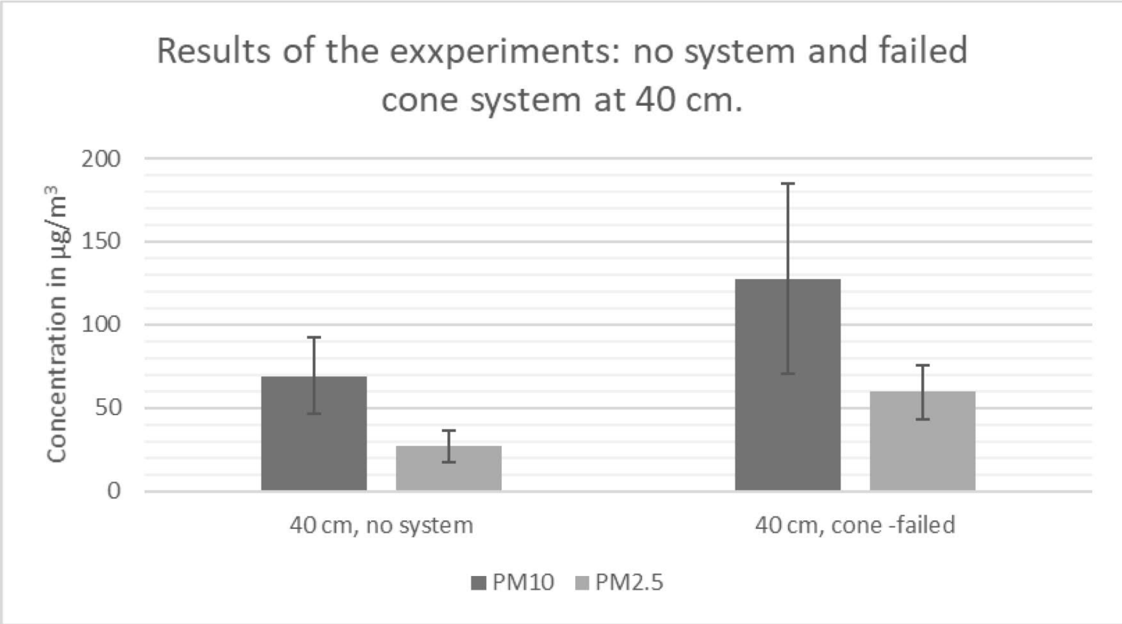


FIGURE 13 Comparison of PM10 (corrected) and PM2.5 concentrations collected by Trotec PC220 at 40 cm above the drone with cone (failed flight) and no systems attached, in µg/m^3.

Trotec PC220 PM10 values collected during the failed flight are half as much as those of the no system flight. The same trend is noticeable with PM2.5 results. Deviation of the results indicated on figure 14 is most significant for PM10 concentrations of failed 40cm cone flight.

5.2.4 Cone inlet system flight at 15cm and failed flight at 40cm

Down below the figure 14 displays results of the experiments of a failed flight of the drone with 40 cm height cone set-up and 15 cm cone set-up. Comparison of the data extracted by Trotec PC220 follows next. Between the flights performed with cone set-ups attached to the drone, results of the performance of 15 cm set-up are more reliable, even by a margin, than results displayed by 40 cm set-up. PM2.5 of the 40 cm cone system flight are higher than those of 15 cm cone system and the collected values of the former deviate more.

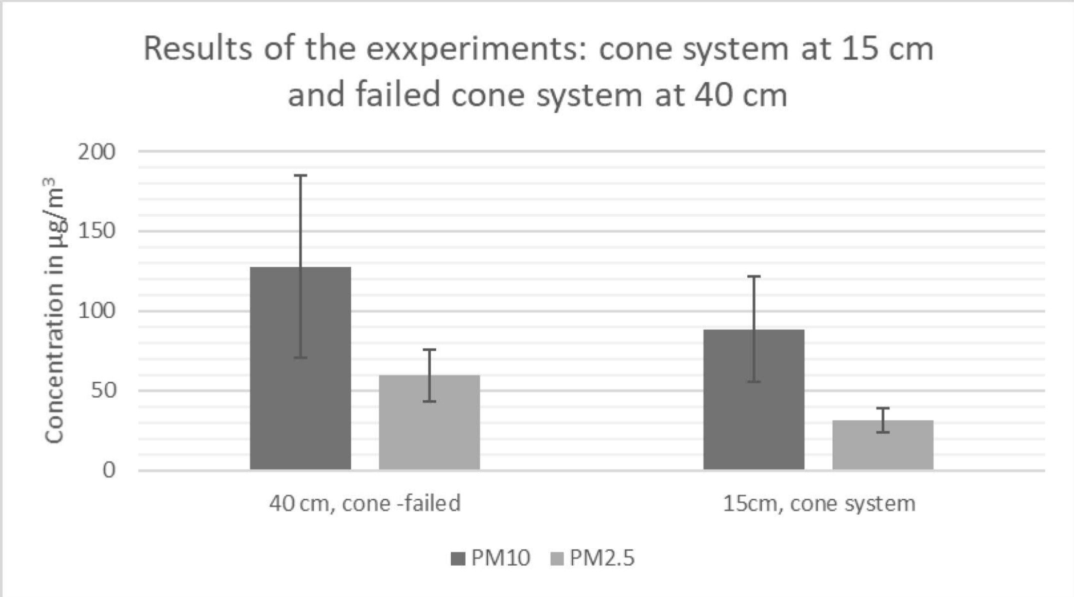


FIGURE 14 Comparison of PM10 (corrected) and PM2.5 concentrations collected by Trotec PC220 at 40 cm above the drone with cone (failed flight) and cone system at 15 cm, in µg/m^3.

Results of Trotec PM10 displayed on the figure 14 have been corrected by DustTak-Trotec dependence displayed in figure 7: y=0,5032x + 20,324. In order to adjust results and make the comparison more comprehensible.

6 DISCUSSION

The results of pollution mapping hinted at possible core problem with either one of the sensors, since Trotec PM10 concentration values were always bigger than those of DustTrak, even though the measurements were taken under same conditions. One of the options for that might have been the present of inlet tube extensions attached to the DustTrak. It can be seen in picture 6. Quick testing of the DustTrak under stable conditions in TAMK laboratory dismissed this assumption. Explanation was found in calibration documentation of both devices (appendix 4 and 5). Apparently, Trotec PC220 had been calibrated only for particle counter, but not for the mass concentration calculation, while DustTrak has been fully calibrated one year ago. In order to adjust the PM10 values of Trotec PC220 to ones of DustTrak, correlation function was used.

First experiment of pollution mapping allowed for the approximation of the settlement rate of the solutions at hand. It took 10-15 minutes for particles to settle below the concentration of 100 µg/m^3 mark. This acquired knowledge determined the rate at which the spraying of the solution occurred during inlet system testing: every 10 minutes after initial spray along the perimeter of the room. Blocked air brush nozzle issue might be the reason for the inconsistency of the measurements, as the solution with particulate matter would be distributed unevenly in some cases.

Height of the installation above the drone, according to figure 10 and figure 11, is most suitable at 15 cm, when compared to 40cm. This observation is surprising, since initially the theory was that with increased vertical distance from the drone, on which the measurement takes place, effect of propellers and air flow will be less influential. This might have occurred because the airflow created by propellers causes additional disturbances in the air higher-up above the drone creating an area not suitable for implementation and creating a buffer zone directly above the body of the drone up until approximately 20 cm. This is only a theory, as there is no research yet done regarding particle behaviour modelling above the drone in flight mode.

Another possibility is that the concentration of the first sample at each measurement is so high because overall concertation of the particulate matter in the laboratory was higher. Speculated reason for such high results of the cone system displayed in figure 12 and 13 is that its shape serves as a funnel for collecting particle as drone takes off vertically. As the drone moves upwards, particles are gathered inside the set-up and the inlet tube, creating more dense sampling probe. This could explain the reason to why the deviation between measurements is so big in experiments involving cone set-ups.

The reason for increased results of the failed flight testing 40 cm cone set-up is the fact that it is essentially a failed flight and conditions for those measurements could not be provided to be even relatively constant. Since the flight was attempted 5 times and measurements were taken continuously, it is hard to evaluate reliability of these results. Plate system was more successful that cone system. Even though it still needs improvements, since deviation in results of plate system testing was more than those of no system flight at the same distance.

There is a trend that could be tracked through all the results. Generally, PM2.5 results are more consistent than PM10. This might be because smaller the size of the particle, it is less affected by the wind on the account of smaller surface area of the particle surface. Mass concentration of PM10 is significantly higher since bigger particles have more significant influence on the values.

For further study of the subject, it would be recommended to substitute air compressor and spray-paint brush with alternative contamination device to provide more controlled conditions for the experiments. Broader variety of the inlet systems can be inspected with different material options. Material would have to be chosen based on weight value, as well electromagnetic properties, to not overload the drone. Alternatively, set of experiments with a smaller sensor could be conducted, for example SPS 30 by Senserion. Although it does require a power source and a connected memory system to function. (Sensirion 2019)

In conclusion, effect, either negative or positive, of the inlet system on the results, is clearly present. From the equipment that was tested during this research, most suitable is the plate system mounted at 15 cm above the drone. However, more

comprehensive studies under stable conditions are required to distinguish the optimal inlet system to be mounted on a drone.

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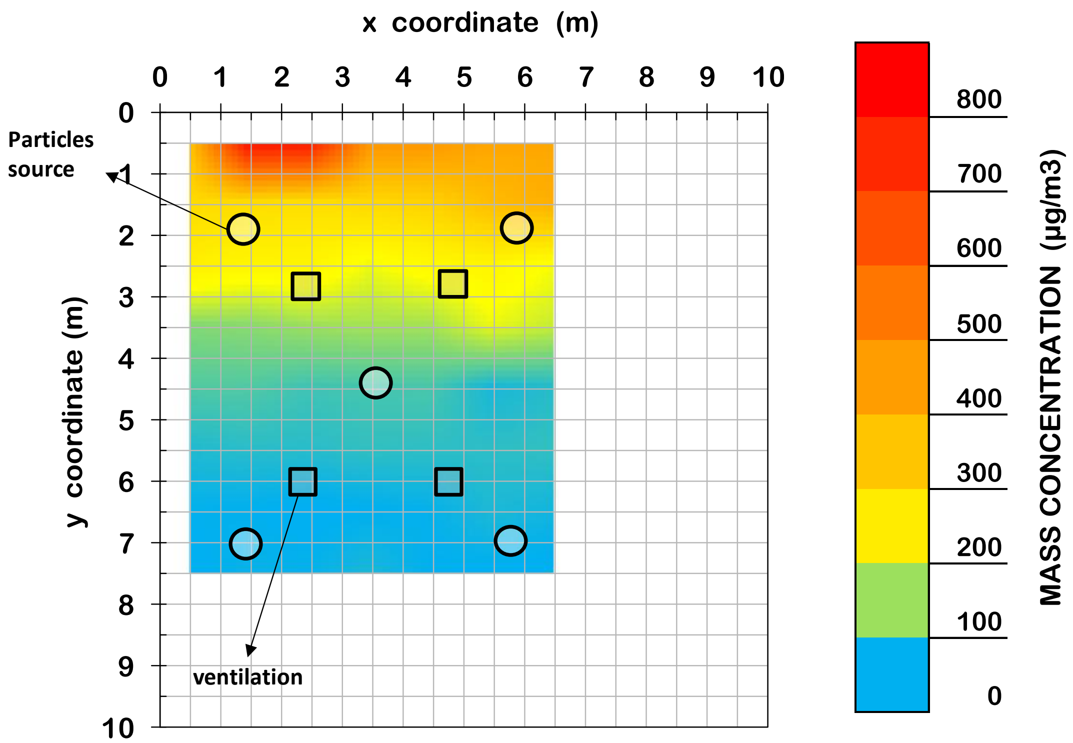
APPENDICES

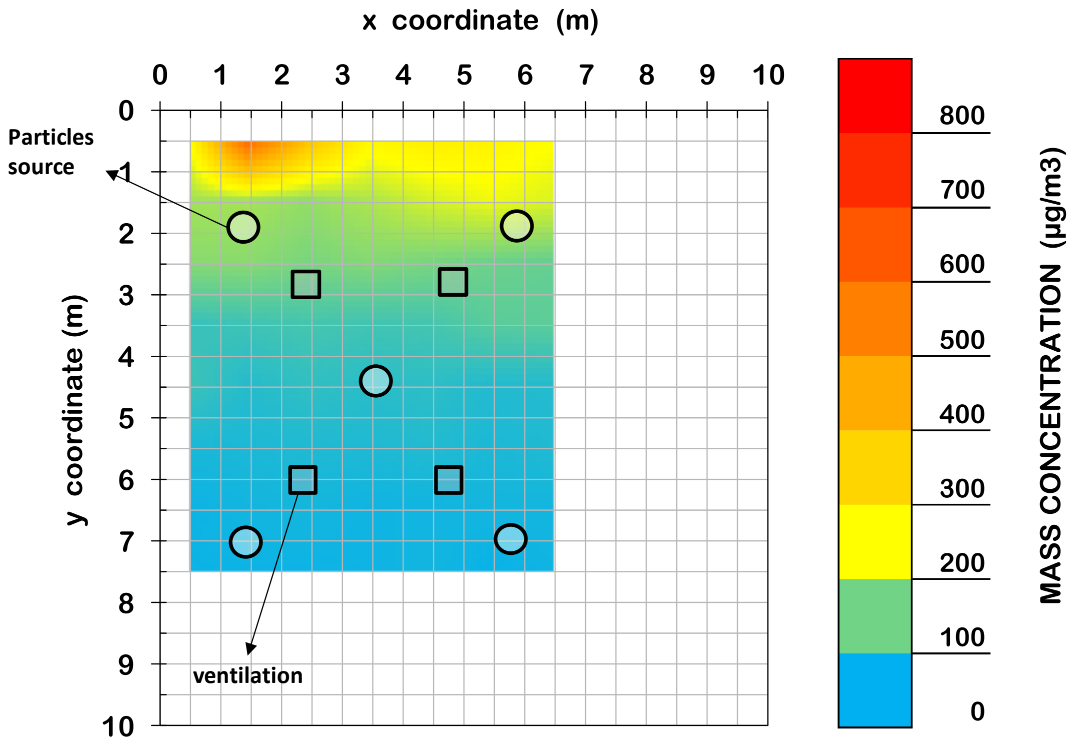
Appendix 1. Colour grid map data sheet (Trotec PM_{10})



MASS CONCENTRATION (µg/m3)

	1	2	3	4	5	6	7	8	9	10	x (m)
1	276	775	762	429	420	382	377				
2	243	240	232	249	267	321	355				
3	193	175	180	144	166	176	149				
4	88	91	101	105	104	140	123				
5	62	62	53	56	58	33	40				
6	37	42	41	46	44	43	46				
7	22	21	17	20	23	35	30				
8	17	25	23	33	21	19	17				
9											
10											
y(m)											

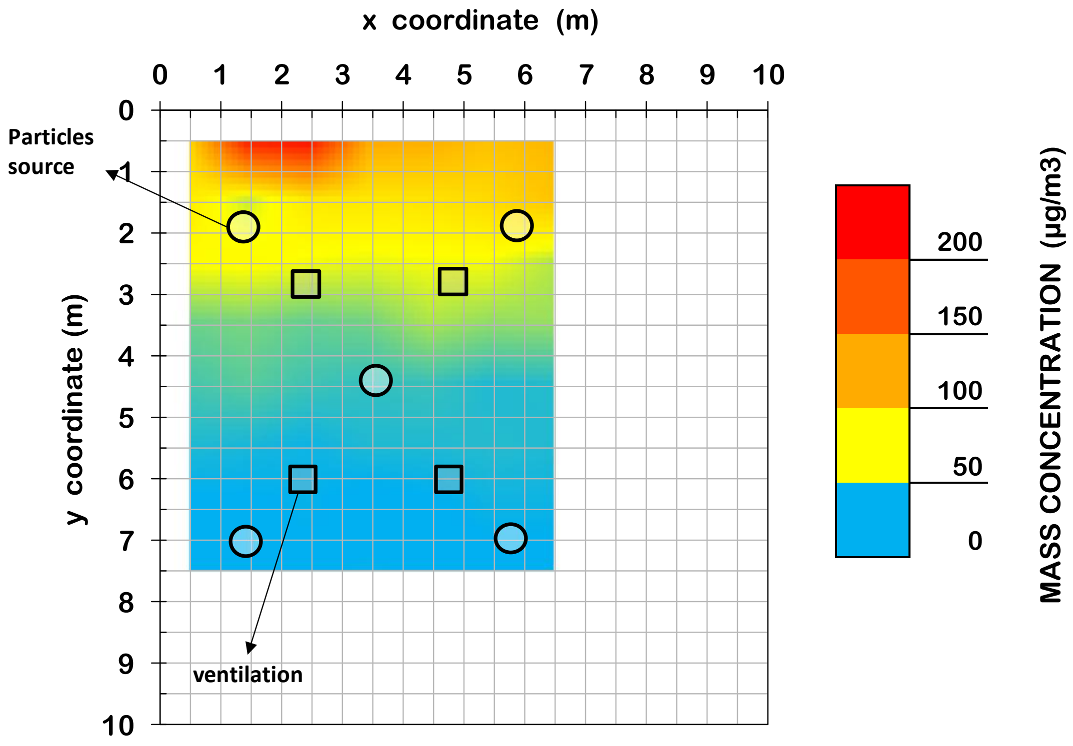
Appendix 2. Colour grid map data sheet (DustTrak PM_{10})



MASS CONCENTRATION (µg/m3)

y(m) \ x (m)	1	2	3	4	5	6	7	8	9	10
1	183	574	354	222	242	229	204			
2	135	138	125	142	170	189	176			
3	117	118	106	114	106	97	92			
4	60	65	70	67	69	84	86			
5	64	47	55	50	52	45	46			
6	39	40	43	42	45	40	43			
7	29	33	35	31	32	34	34			
8	28	29	29	30	33	27	31			
9										
10										

Appendix 3. Colour grid map data sheet (Trotec $PM_{2.5}$)



MASS CONCENTRATION (µg/m3)

		1	2	3	4	5	6	7	8	9	10	
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**x (m)**
1	**1**	68	190	198	102	99	87	93				
2	**2**	62	42	63	64	66	72	84				
3	**3**	51	53	49	47	49	49	39				
4	**4**	27	29	26	28	37	33	34				
5	**5**	21	24	20	18	19	15	16				
6	**6**	15	14	12	15	15	16	15				
7	**7**	9	9	11	7	9	12	12				
8	**8**	9	8	9	11	9	8	8				
9	**9**											
10	**10**											
	y(m)											

Appendix 4. Certificate of Calibration and testing of DustTrak from TSI.

Certificate of Calibration and Testing

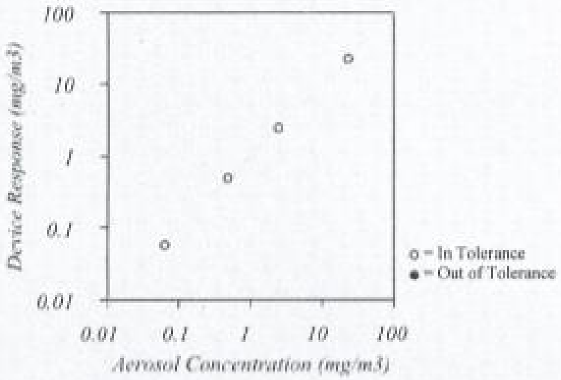
TSI Instruments Ltd, Stirling Road, Cressex Business Park
High Wycombe Bucks HP12 3ST England
Tel: (Int +44) (UK 0) 1494 459200 Fax: (Int +44) (UK 0) 1494 459700 http://www.tsiinc.co.uk

Environment Conditions		
Temperature	20.5	°C
Relative Humidity	47.02	%RH
Barometric Pressure	1017.6	hPa

Model	8520
Serial Number	14210

☒ As Left ☒ In Tolerance
☐ As Found ☐ Out of Tolerance

Concentration Linearity Plot



System ID: DTH02-01

Zero Stability Results

Average:	Minimum:	Maximum:	Time:
0·001 :mg/m³	0·000 :mg/m³	0·002 :mg/m³	2·10 :hrs.

TSI Incorporated does hereby certify that all materials, components, and workmanship used in the manufacture of this equipment are in strict accordance with the applicable specifications agreed upon by TSI and the customer and with all published specifications. All performance and acceptance tests required under this contract were successfully conducted according to required specifications. There is no NIST standard for optical mass measurements. Calibration of this instrument performed by TSI has been done using emery oil and has been nominally adjusted to respirable mass per standard ISO 12103-1, A1 test dust (Arizona dust). Our calibration ratio is greater than 1.2:1

Measurement Variable	System ID	Last Cal.	Cal. Due
Barometric Pressure	E006180	09-05-17	09-05-18
Humidity	E006182	09-05-17	09-05-18
Microbalance	UK WB13D0013	04-01-17	04-01-18
Pressure	E006180	09-05-17	09-05-18
DC Voltage	E003323	09-05-17	09-05-18

Measurement Variable	System ID	Last Cal.	Cal. Due
Temperature	E006182	09-05-17	09-05-18
Photometer	E003336	11-09-17	11-03-18
Flow and Temperature	E006128	16-01-17	16-01-18
DC Voltage	E003322	10-05-17	10-05-18

Calibrated

☐ Final Function Check

22 December, 2017
Date

Appendix 5. Certificate of test report for Trotec PC220 1(2)

Werkskalibrierzeugnis
Calibration test report
Certificat d'étalonnage

Hiermit wird bescheinigt, dass dieses Trotec-Erzeugnis in Übereinstimmung mit dem QM-Handbuch der Trotec GmbH & Co. KG nach DIN EN ISO 9001/9002 gefertigt wurde. Die Bestellvorgaben wurden eingehalten. Die Ausführung und Anzeigegenauigkeit der Geräte/Systeme wurde im Rahmen der Trotec Kalibrier- und Qualitätssicherungsmaßnahmen überwacht. Die Kalibrierung des Gerätes erfolgte gemäß ISO 21501-4.

This is to certify that this Trotec product has been made according to the TQM to the Trotec GmbH & Co. KG manual in accordance with DIN EN ISO 9001/9002. Ordering specifications are complied with. Execution of instruments / systems as well as testing of accuracy was carried out following Trotec calibration and quality assurance procedures. Item calibration has been made corresponding to ISO 21501-4.

Par ce document, nous certifions que votre produit Trotec a été fabriqué suivant les normes TQM de Trotec GmbH & Co. KG en concordance avec DIN EN ISO 9001/9002. Les spécifications stipulées dans la commande ont été appliquées. La réalisation des appareils/systèmes ainsi que les tests de précision ont été réalisés dans le cadre des procédés de qualité et d'étalonnage Trotec. L'étalonnage de l'appareil a été réalisé conformément à ISO 21501-4.

Typ/Type/Type: **PC220**

Genauigkeit/Accuracy/Précision:

Particle:	accuracy ±30 %
	counting efficiency 50 % @ 0.3 µm; 100 % for particles >0.45 µm
HCHO:	±5.0 % FS*
CO:	±5.0 % FS*
T:	±0.5 °C (0.9 °F) 10 °C to 40 °C
	±1.0 °C (1.8 °F) others
RH:	±3.0 %RH (40 % to 60 %)
	±3.5 %RH (20 % to 40 % and 60 % to 80 %)
	±5.0 %RH (0 % to 20 % and 80 % to 100 %)

Serien Nr./Serial Nr./N° de série: 180410530

Kalibriereinheit (Referenz)/Calibration unit (Reference)/ Équipement d'étalonnage (référence):

Fabrikat/ brand/Modèle:	LIGHTHOUSE 402999220-1/FLUKE 985
Zertifikat-Nr./Certificate-No./ N° de certificat	175104806
Serien Nr./Serial Nr./N° de série	51000020 / 1210993188
Genauigkeit/Accuracy/Précision:	+/10%um
Kal.-datum/Cal.-date/ Date d'étalonnage	2017-9-30
Standards/Standards/Normes:	JJF1190-2008

*FS = Full Scale

Umgebungsbedingungen/Environmental conditions/ Conditions environnementales:

Temp [°C]: 25,0 ℃

Rel. Hum [%]: 51,0 %RH

Datum/Date/Date: 2018-4-18

Messergebnisse/Measuring results/Résultats: Particle

Nr.	Messbereich/ Range/ Plage de mesure [µm]	Referenz/ Reference/ Référence [n]	Toleranz/ Tolerance/ Tolérance [%]	Messwert/ Reading/ Valeur mesurée [n]	Abweichung/ Deviation/ Écart [% (n)]	Status/ Status/ Résultat
1	0.3	105378	+/-30	102726	-3% (-2652)	Passed
2	0.5	32141	+/-30	31187	-3% (-954)	Passed
3	1.0	4726	+/-30	4497	-5% (-229)	Passed
4	2.5	428	+/-30	452	6% (+24)	Passed
5	5.0	78	+/-30	79	1% (+1)	Passed
6	10	21	+/-30	26	24% (+5)	Passed

Messergebnisse/Measuring results/Résultats: HCHO

Nr.	Messbereich/ Range/ Plage de mesure [PPM]	Referenz/ Reference/ Référence [PPM]	Toleranz/ Tolerance/ Tolérance [%]	Messwert/ Reading/ Valeur mesurée [PPM]	Abweichung/ Deviation/ Écart [%]	Status/ Status/ Résultat
1	0.01-5.00	0.25	+/-0.25	0.21	-0.04	Passed
2	0.01-5.00	0.40	+/-0.25	0.41	+0.01	Passed

Messergebnisse/Measuring results/Résultats: CO

Nr.	Messbereich/ Range/ Plage de mesure [PPM]	Referenz/ Reference/ Référence [PPM]	Toleranz/ Tolerance/ Tolérance [%]	Messwert/ Reading/ Valeur mesurée [PPM]	Abweichung/ Deviation/ Écart [%]	Status/ Status/ Résultat
1	10-1000	420	+/-50	415	-5	Passed