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MULTIROTOR PLATFORM WITH SENSORY HEAD FOR MEASUREMENT OF SELECTED AIR PARAMETERS

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Abstract

In this article, a project of an unmanned aerial system designed for monitoring of air pollution is presented. The system consists of an autonomous unmanned aerial vehicle (UAV) equipped with a measurement head with sensors of chemical and physical properties of atmospheric air, and a ground control station arranged to store and display the collected data. The head contains modern sensors selective to the most important components of air in view of environmental pollution. Measurement data are acquired locally as well as transmitted wirelessly to a ground station. The UAV can be programmed to a particular measurement missions. The ground station dispose of a software for flight control and for visualisation of measurement results on-line. In this paper, an architecture of the entire system, a data processing performing by each subsystem, and communication methods between them are presented. This paper also includes a specification of sensors with their principles of operation, description of their metrological properties and the way, in which they are implemented in the designed electrical circuits. Results of preliminary tests in a laboratory and in a field, during a short flight, are also presented.

Keywords: *Unmanned aerial vehicle, pollution measurement, on-line air monitoring, environmental monitoring, embedded gas sensing system*

1. Introduction

The issue of air pollution is a problem, which has been addressed, by environmentalists, doctors and engineers for many years. Despite all the efforts applied by political organisations and private companies, the air quality in heavily urbanized areas still cannot be considered as acceptable. Very important matter is a possibility to monitor the presence and concentrations of substances undesirable in the atmosphere with highest possible accuracy, on widest possible area and with lowest possible effort. Stationary stations for controlling pollution levels provide accurate measurements of many physical and chemical air properties, however, their construction cost is very high, and the measurement takes place only in one spot.

In order to monitor the environmental quality in wider area, mobile immission measurement ambulances can be used [9], but the cost of such investment is still very high, and it is impossible to monitor the vertical gradient of measured parameters on altitudes higher than a few meters. To eliminate these disadvantages, there are created many experimental ways of measurement. One of them is a multirotor unmanned platform equipped with a probe head containing integrated sensors of numerous chemical and physical air parameters.

It is a novel idea, currently being implemented in London, to equip pigeons with small measuring devices with GPS modules [4]. However, it allows only for imprecise measurement of a single parameter, and the location of the measurement is non-deterministic.

A multirotor unmanned platform equipped with an appropriate set of sensors provides a solution, which combines the advantages of all aforementioned approaches. A probe head equipped with integrated sensors of nitrogen and sulphur oxides, carbon monoxide, particulate matter, ozone, benzene, and basic physical properties of air, can be compact enough to allow for its installation on board of a drone, with accuracy sufficient to produce data useful for analysis of air pollution. The advantages of this approach allow it to be used in numerous applications, such as [5, 6]:

- local concentrations measurement of selected air parameters (residential areas, economic zones, spoil tips, workplaces, etc.),
- measurements in random time and place,
- locating objects harmful to the environment, as well as assessment of their nuisance,
- construction and verification of mathematical models of pollutant dispersion in the atmosphere,
- preliminary assessment of the occurrence of fire,
- 3D mapping of the concentration of the target gas,
- preparation of the data for the analysis of spatial development plans of the country and location decisions of new investments,
- assessment and analysis of local exceedances of air pollution standards,
- verification of the effectiveness of atmosphere protection programs,
- monitoring the emission of pollutants along roads (highways, nodes) in peak hours.

This kind of platform can be used not only to measure the overall state of the atmosphere, but also to analyse the content of exhaust gases from household furnaces and fireplaces. The smog originating from these sources is a growing problem in many agglomerations, but there are no effective methods quickly to verify whether the fuel used in a household is in accordance with the standards and regulations. A platform equipped with sensors of characteristic combustion-source substances would allow for a fast and non-invasive preliminary verification of the type of fuel and provided the basis to take further steps, such as ash sample collection and analysis.

The main aim of this research effort is:

- to develop and construct the multirotor unmanned platform as a carrier of sensory head,
- design and construction of a prototype of dedicated sensory head for measurement of selected air parameters.

2. Unmanned aerial system

The aim of the project is to design, develop and manufacture hardware and software for an Unmanned Aerial System (UAS), which consists of

- Unmanned Aerial Vehicle (UAV) – a multirotor platform, hexacopter (Fig. 1), with autopilot and equipped with a sensory head intended for measurements of selected air parameters,
- Ground Control Station (GCS).

Multirotors have become very popular and have a few advantages over other types of drones e.g. unmanned planes [2, 10]. The ability to start and land vertically gives them a possibility to operate in a small, hard to reach and hazardous areas. They are characterized by high versatility and the ability to perform very specific tasks. The hexacopter has been constructed with the following guidelines:

- payload 500 g,
- dimensions of sensory head 10x10x5 cm,
- possibility of easy replacement of measurement modules,
- flight time approx. 20 min.

The autopilot function has been entrusted to ArduPilot APM 2.6, whereas the Mission Planner application acts as a GSC. Software of both autopilot and GCS has been significantly modified. Autopilot functionality has been extended to communication and data exchange with sensory head, which is described in the next chapter, and cooperation with a vision system. The vision system allows, in real-time, for the preview of the environment in which the UAV is operating with the possibility of correcting the orientation of the gimbal. After the modification of a flight controller software, it receives the package of pre-processed digital data, which includes both telemetry and indications from the air quality sensors via UART interface. Then, that package is sent to the GCS application by means of long-range wireless link. GCS software provides interface and visualisation capabilities, which can be highly helpful during the UAV mission. It is essential to receive and show the ground operator not only flight parameters, but also data from the sensors. These data are prepared beforehand and send by the autopilot. Measurements of individual air parameters are sent to the GCS in the modified data frame and presented in graphs taking into account the spatial location. It allows adding to the GCS application further features – showing the measurement results directly on a map and on a time chart. The measurements are assigned to each spatial location including the height, allowing to mark the information on a map of the area or to visualise them e.g. in the form of a 3D map. The platform has the ability to perform missions in either manual or automatic mode – the operator is able directly to control the device or to program the route as a list of coordinates of measurement points.

Fig. 1. Multirotor platform

The final result of the work is a prototype of UAS consisting of hardware modules with a measurement system, control algorithms and data processing, allowing equipping UAV with necessary technical means to perform specified tasks.

3. Sensors and substances

3.1. Substances

Air pollution is an introduction of particulates, biological molecules or other harmful materials into Earth's atmosphere, which can negatively affect human health, climate, wildlife, soil, water or cause other damage to the environment. Among the most commonly monitored air pollution is:
- carbon monoxide,
- nitrogen oxides,
- sulphur dioxide,
- tropospheric ozone,
- particulate matters $PM_{2.5}$ and PM_{10},
- benzene,
- benzopyrene,
- heavy metals (lead, arsenic, cadmium, nickel, mercury).

These compounds are under special observation due to a very negative impact on the environment and the human body, and the fact of their continuous emission to the environment by industrial processes and exploitation of fossil fuels.

Carbon monoxide is one of the main products of combustion process. It is highly poisonous, colourless, odourless, and tasteless gas, which usurps the space in haemoglobin that normally carries oxygen, causing hypoxia that results in the damage of circulatory and nervous system.

Nitrogen oxides, mainly NO and NO_2, in contact with water form nitric acid. When this reaction occurs in the atmosphere, it results in acid rains, having a destructive effect on the environment. When these gases get to human airways, they cause tissue damage leading to such diseases as bronchitis and emphysema. A sulphur dioxide has very similar effect, as well as being able to enter the blood stream and cause damage to organs such as the liver, spleen or brain.

Ozone, triatomic oxygen, is normally present in the upper atmosphere, mainly stratosphere. Tropospheric ozone is a pollutant, arising mainly as a result of photochemical reactions of nitrogen oxides, carbon oxides, and hydrocarbons derived from anthropogenic sources. Ozone can cause irritation of the respiratory tract and eyes, chest pain, irritation of mucous membranes, and respiratory diseases.

Particulate matters PM_{10} and $PM_{2.5}$ are a mixture of all particles suspended in the air less than 10 microns and 2.5 microns, respectively. They have the ability to enter the lungs, resulting in poisoning, upper respiratory tract inflammation, pneumoconiosis, lung cancer, allergic diseases and asthma.

Benzene and benzopyrene are compounds that release into the atmosphere as a result of the combustion of fossil fuels and contained in cigarette smoke. Both are highly carcinogenic. Heavy metals have the ability to accumulate in tissues and cause poisoning and organ damage.

3.2. Measurements

Concentration of the above-mentioned compounds in the air is constantly monitored by appropriate environment-protecting institutions. Considering the way in which they are performed, measurements can be divided into the following groups:

- Automatic – Measurements of gas samples are performed continuously by online working sensors. Thanks to direct analysis, it is possible to get results in any moment,
- Manual – Aspirators are used and pollutants are extracted from the air by selective filters or scrubbers, which absorb certain substances. Then, the collected sample is analysed in a laboratory,
- Passive – Absorbents placed on measuring stations for a long period of time (approx. one month) are used. During that time, pollutants are absorbed on the surface of the filters, and then the filters are sent to a laboratory for further analysis.

In most cases, the most practical is automatic measurement – requires no operator intervention, and the results are available continuously. Unfortunately, not all of those substances can be detected in this way due to their characteristics, and uncertainties of such measurements are usually higher, it means worse, than those obtained in laboratory conditions. Automatic measurements are usually used to examine the concentration of carbon monoxide, nitrogen oxides, sulphur dioxide and ozone, less frequently benzene, particulate matter and gaseous mercury [8].

The device described in this paper is designed to perform an automatic measurement – its head is equipped with electrical sensors responsive to different concentrations of compounds in a continuous way. It is planned in the future to adapt the device to perform manual measurements – bearing capacity of the platform is sufficient to take adequate aspiration systems and tanks, allowing the device to collect the air samples for later analysis.

3.3 Types of sensors

Sensors that can be used in this project should be characterized by small size and mass. These properties exclude from the scope many available constructions of gas sensors, such as interferometric sensors, flame ionisation detectors, photoionization detectors. Among types of

sensor, which fulfil the criteria, the most popular are:
- tin oxide semiconductor sensors,
- electrolytic sensors,
- nondispersive infrared sensors.

The principle of operation of metal oxide semiconductor sensors bases on increasing of conductivity of a sensing element depending on the gas concentration in the air. There are usually made of tin oxide with other metal oxides or precious metals dopants. It makes the sensor sensitive to specific compounds or group of compounds. However, this types of sensor are not very selective – usually they response to a few different gases, which in some situations can be an advantage. To obtain the best possible metrological properties, this type of sensors usually works in stabilized, higher temperature, provided by built-in heater [3].

Electrolyte sensors consist of a plastic tank filled with appropriate electrolyte with two to four electrodes, which can be connected to external electrical circuit. The tank is closed by a capillary tube, which allows influence of a gas to the interior of the sensor. When detected compound appears in sensor's surroundings (and diffuses to the electrolyte), the electrical potential, dependent on gas concentration, occurs on electrodes [1].

Nondispersive infrared sensors consist of an infrared source, filters, a reference chamber, a sample chamber and a detector. An infrared light beam is directed through the sample chamber, where the gas closed in the chamber causes an absorption of specific wavelengths according to the Beer-Lambert law. The reference chamber is filled with known concentration of analysed gas. The ratio of absorptions between sample and reference chamber allows determining the gas concentration [7].

Tab. 1. List of used sensors

Parameter	Name	Sensor type	Range	Uncertainty
O_3	Ozone	MQ-131	10-2000 ppb	not definied
CO	Carbon oxide	TGS5342	0-1000 ppm	2 ppm
NO_2	Nitrogen dioxide	NAP-550	0-30 ppm	2% of signal
PM	Dust	GP2Y1010AU0F	0-500 µg/m^3	not defined
Temp, RH	Air temperature and humidity	DHT22	-40- -80 ºC 0-100 %RH	0.5 ºC 2 %RH

4. Prototype of sensory head

The sensory head, which is currently being designed, consists of a two layer printed circuit board (PCB) (Fig. 2), and has a compact structure with the ability to add auxiliary modules in the future (e.g. TGS 2000 family). Currently, it is intended to measure the following substances: CO, O_3, $NO/NO_2/NO_x$, $PM_{10}/PM_{2.5}$. Additionally, the device is equipped with a piezoelectric buzzer, which allows for immediate alarm signalling in case of serious contamination detection. The accepted range of power supply voltage is from 10 V to 20 V, which covers most popular 2S and 3S lithium polymer battery configuration. The design also allows for a direct connection to PC by means of serial USB port emulation, which, in turn, allows for desktop use and laboratory testing. All digital and analogue interfaces are governed by a state-of-the-art microcontroller from STM32 family running at 72 MHz clock. Due to the fact that most of the sensors have analogue outputs, signal conditioning for all of them include low input current and low offset voltage operation amplifiers, which provide important output impedance decoupling for microcontroller.

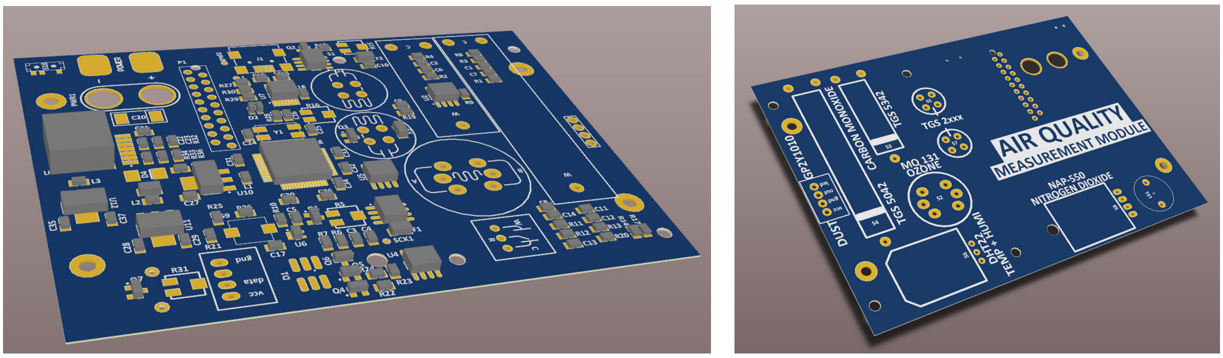

Fig. 2. Renderings of the applied printed circuit boards

The main features of the measurement instrument are the low power consumption and the small form factor, achieving long duration of flight. The measurements are assigned on the ground station to each spatial location including the height, allowing to mark the information on a map of the area or to visualise them e.g. in the form of a 3D map. The platform has the ability to perform missions in either manual or automatic mode – the operator is able to control directly the device or to program the route as a list of coordinates of measurement points.

The main difficulties in the construction of this type of platform are disturbances. The performance of the sensors, mostly electrochemical, can be negatively affected by factors such as electrical and electromagnetic interferences coming from the working engines, the vibrations of the whole system, and air streams caused by the rotors. The interferences can be minimized through an appropriate design of the platform, position of the measuring head, and selection of sensor with the smallest possible sensitivity to these factors.

5. Architecture of control and measurement system

The designed system contains elements of a control system responsible for controlling the movement of the multirotor platform and control of the sensory head. The designed on-board system has two basic functions:

- flight control taking into account different levels of autonomy (modes of operation),
- measurements of individual air parameters.

The control architecture in such a large system (Fig. 3) has been designed as a robust and decentralized system distributed between a hexacopter and GCS. Due to the functionality of control system, advancement level of the flight operator and a given tasks related to the performed mission, UAS can operate in one of two modes of flight: manual or automatic mode – the operator is able directly to control the device or to program the route as a list of coordinates of measurement points.

System communication is bidirectional. The operator is able to control the UAV directly using a remote control system. An autonomous flight is planned in the ground control station, from which waypoint coordinates are transmitted to the on-board flight controller.

Measurement data coming from the sensors are pre-processed in a signal conditioning circuit according to sensor manufacturer guidelines. Both MQ-131 and TGS2xxx modules are standard heater and sensing resistance devices, which are very robust and versatile. They also perform well in terms of stability in long term and wide detection range. Each of them has a separate potentiometer in order to set a correct sensing load. Carbon monoxide sensing modules are, on the other hand, current source devices, which require current to voltage conversion via an operational amplifier integrated circuit. In terms of signal conditioning, the most sophisticated turned out a nitrogen dioxide NAP-550 module, which offers reference electrode pin for the user. This feature helps to extend working range of the sensors and improves linearity of the measurement. On the other hand, it requires the most caution in terms of PCB design around sensitive analogue outputs.

The simplest to interface is DHT22, which communicates by serial interface. Finally, the dust particle content sensor requires initiating LED backlight and in return outputs analogue voltage proportional to air contamination.

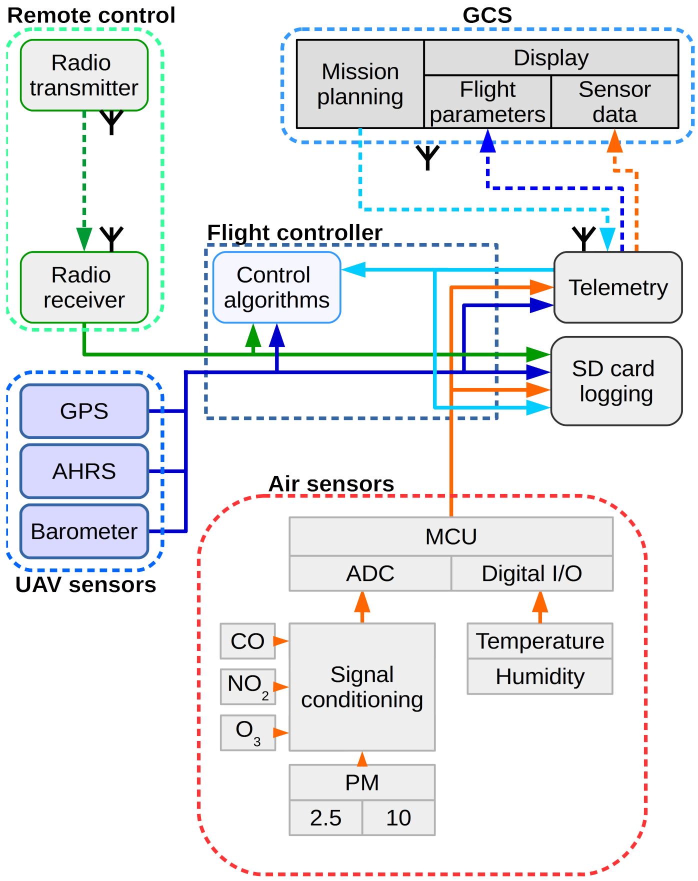

Fig. 3. Architecture of the control system; MCU Microprocessor Control Unit; ADC – Analog to Digital Converter; Digital I/O – Input/output for digital sensor signal; GPS – Global Positioning System; AHRS – Attitude and Heading Reference System

The microcontroller unit acquires all the measurement results, converts them to an appropriate digital frame packet format and transmits to the flight controller. The autopilot subsystems log air sensors data to SD card and transmit it back to the ground via telemetry link along with other flight parameters.

6. Results

The UAS was examined in a laboratory and in a field. All mechanical and electrical components were put together and tested. A response of a CO sensor on a concentration step is presented in Fig. 4. The obtained t_{90} time is about 60 s. An example of measurement data collected above a forest, a motorway and housing estates are presented in Fig. 5. The distance is about 500 m. Concentration of CO in air expressed in ppm are visualised using colour balloons put on a map. The insert in the figure contains a time changes of the concentration during the flight. The map may be placed close to an autopilot window allowing the operator of UAV to preview the measured parameters.

The mechanical construction, electronics, control algorithms and software work well, however the measurement results are still unsatisfactory. The problem is disturbances, which are significantly higher than the change of the measurement signal. Further works on filtering, both electrical and numerical, as well as on shielding, are needed.

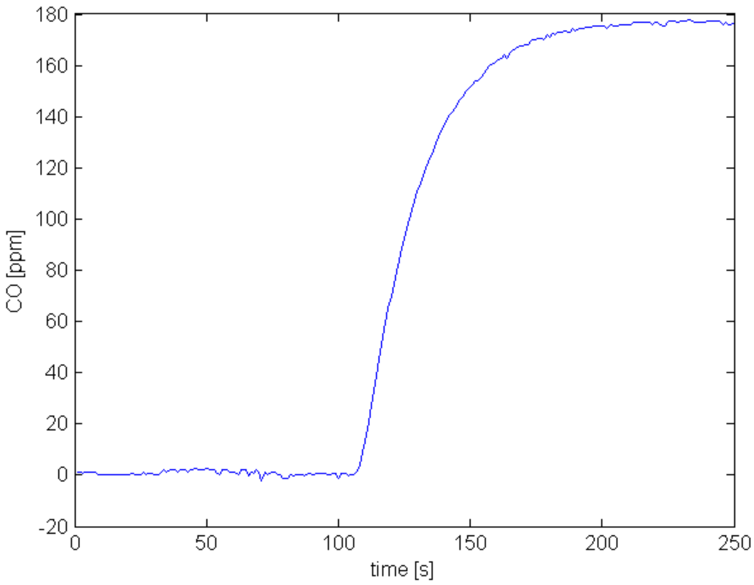

Fig. 4. Time answer of CO sensor on concentration step obtained during laboratory tests

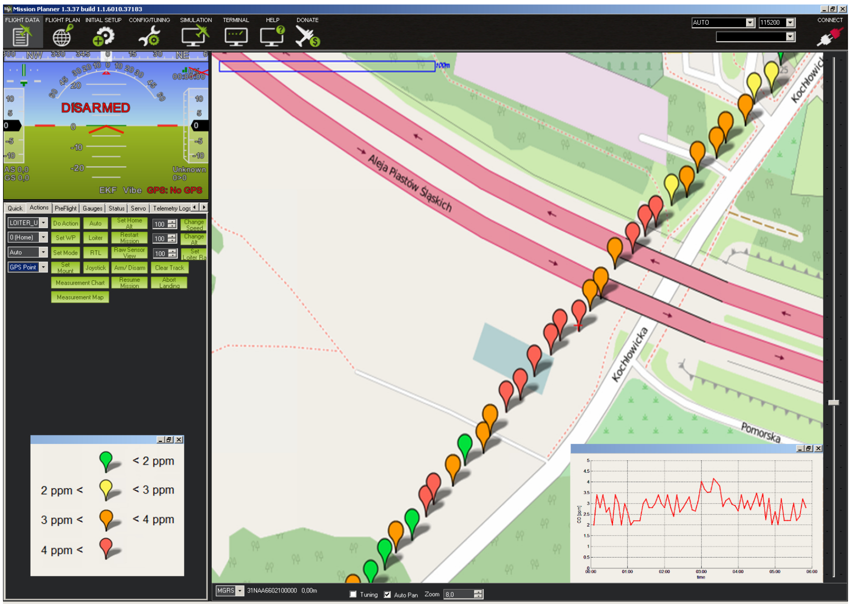

Fig. 5. Map of monitored area with time plot of CO results

7. Conclusion

In this paper, a complete concept and prototype of UAS for measurement of selected air parameters is presented. An embedded system for environmental monitoring consists of an unmanned multirotor platform, a sensory head with smart devices, a ground control station and a data link infrastructure. The architecture of the control and measurement system allows for both visualisation of measured data during a flight mission, and also storage of measured values for later analysis. In order to ensure functionality of the system, the software-components of both ArduPilot APM 2.6 as an autopilot and Mission Planner as a ground control station has been significantly modified, whereas the hardware of the sensory head has been designed from scratch. The main features of the measurement instruments are the low power consumption and the small form factor, achieving long duration of flight. First tests perform in a laboratory as well as in a field promise a robust and accurate monitoring of air pollution in various scenarios.

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