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Atmospheric Boundary Layer Dynamics Evaluation Using Piezo-Resistive Technology for Unpowered Areal Vehicles

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ABSTRACT

The paper presents a method for real-time observing of the convectional processes in the atmosphere boundary layer. The essence of the method is in providing real-time measurement of temperature, humidity, and pressure during the flight of a glider (soaring flight). Based on these measurements, a real-time evaluation of the atmosphere dynamics is presented. Measurements are taken during soaring flight of the glider and during the flight of a remotely controlled quadrocopter. Additionally, a method for atmosphere thermal identification by the measured parameters is introduced. The main application areas of this work are in unpowered flights, as well as in extending the flight time and distance of powered aerial vehicles. Moreover, the paper can be useful in research and observation of the lowest portion of the atmosphere and micro-scaled atmosphere dynamics evaluation.

KEYWORDS

Atmosphere Thermals, Convective Lift, Digital Sensors, Gliders, Laps Rate, Micro-Scaled Atmosphere Dynamics, Real-Time Evaluation, Soaring

1. INTRODUCTION

Measuring pressure, temperature and relative humidity *fast enough* in order to provide real-time information of the momentum state of the atmosphere plays an important role in navigation and instrumentation applications for soaring gliders and in UAV

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(Unmanned aerial vehicles) (Akhtar, Whidborne, & Cooke, 2012). This is achieved via suitable electronics for providing online information to the pilot inside the UAV cockpit (Reddy, Celani, Sejnowski, & Vergassola, 2016). However, as we are aware, appropriate *light-weight multy-sensory systems* for paragliders, for example, have not been designed yet, and the pilot relies on intuitive decisions most of the time of the soaring flight.

Sensors with low power consumption, digital interfaces, miniature and light-weight packing, based on piezo-resistive technology such as Bosch Sensortec BME280, for example, are available at a low-cost price today and can be implemented in the multi-sensory system (MSS) for assessment of the momentum state of the atmosphere. At the same time, mathematical processing of the data is necessary in order to accomplish the micro-scaled dynamics evaluation in order for the multi-sensory system to implement intelligence solutions to provide better cognitive support to the pilot rather than just displaying raw data. One promising approach is based on ornithology studies (Laurenza, 2007), since the soaring of a glider and a bird share many commonalities like – being lightweight, motor-less, relying on current atmospheric dynamics at low altitude of flight.

Numerous accounts of birds soaring without flapping their wings, ranging from observations by Leonardo da Vinci to Octave Chanute can be found in the literature (Laurenza, 2007). Birds circling in thermals are typical examples for the advantageous use of the atmospheric energy to preserve one's position in the air (Ákos, Nagy, Leven, & Vicsek., 2010). For instance, nowadays different types of gliders are soaring thermals and reaching hundreds of kilometers and dozens of hours in the air in a single unpowered flight (Pagenan, 1992).

It is well known that there are different forms of energy in the atmosphere boundary layer (Ákos, Nagy, Leven, & Vicsek., 2010). Some of them are stronger, but less predictable than others. Dynamical forms of energy can be found in:

1. Ridges (orographic lift, where the slopes of hills and mountains deflect wind);
2. Atmospheric thermals (uneven heating of the ground, which produces buoyant instabilities);
3. Waves (long period oscillations of the atmosphere, which occur in the lee of large mountain ranges). These waves were used in the altitude flight record by Airbus Perlan Project, for example, (https://www.airbus.com/newsroom/press-releases/en/2018/09/airbus-perlan-mission-ii-glider-soars-to-76-000-feet-to-break-ow.html). In recent years also theoretical and experimental investigations of energy extraction from atmospheric turbulence are performed with main application large aircrafts (Patel & Kroo, 2008). With UAV, however, the forms of energy, influencing the flight, differ in scale and dynamics, which needs further investigation and modeling.

The *atmospheric thermals* are the most commonly used forms of energy for soaring flights. Although they occur frequently and over various types of terrains, in both hilly and flat areas. Their nature is not understood well, which has led to a number of casualties with light planes without being able to define the exact reason for this to occur (Pagenan, 1992).

Our hypothesis is that providing further investigation of the atmospheric boundary layer dynamics can contribute substantially to the safety of the flights. Thus, the present paper is focused on the evaluation of the atmosphere boundary layer dynamics on *a micro-scale*, since exactly in this boundary layer most of the soaring flights are performed.

Successful soaring requires efficient optimization and skillful localization of the atmospheric thermals by the pilot or by the multi-sensory system for flight evaluation. At the same time, using thermal energy in the atmosphere is a difficult and complex task, not fully understood and not well defined. Although each thermal is unique in terms of size, shape, and strength, the following steps should be met in order to optimize the flight, according to (Akhtar, 2011):

1. Locating the thermal;
2. Entering the thermal;
3. Centering the thermal;
4. Leaving the thermal efficiently and at the right moment.

Note that the main aim of a soaring flight is to gain as much altitude as possible and to reach this altitude *fast enough*. Achieving an optimal trajectory between thermals, downdrafts and turbulent area is the second, complementary aim to the main one.

Decision-making requires evaluating the existence of a stronger thermal, or considering the existing near and more convenient updrafts. Thus, the main *objective* of the present study is to demonstrate that the strength and size of an atmospheric thermal affects the expected altitude gain from it. The stronger a thermal is, the greater the lift effect on the unpowered glider. This statement is proved empirically here, by performing field tests of flights in a paraglider by the first author of the paper.

The remainder of this paper is organized as follows: Section 2 discusses related work and outlines the novelty of the proposed approach. Section 3 presents the method for real-time evaluation of the atmosphere boundary layer, including proof of the hypothesis. Section 4 introduces the developed system based on combined piezo-resistive digital sensor and describes how the experimental measurements are performed. At the end of this section the main results are presented and discussed. The conclusion section outlines some future work.

2. RELATED WORK

It is well known that a thermal is a *collection of air particles* rising through the general mass of air because it is lighter than its surrounding particles. Cone (1964) approximates a free thermal to a buoyant vortex ring system in which the ratio of the ring to the core radius (*R/a*) is less than ten. Our model of the atmosphere air dynamics is similar as so called "bubble theory" defined by Scorer (1957), and the paper is based on the fundamental research of Scorer (1957) and Cone (1964).

Some approaches for measuring, evaluation and analysis of air convections are reported in the literature such as: Numerical simulations for modeling of atmosphere dynamics (Hernandez-Deckers & Sherwood, 2016); "Doppler" radar for measurements of vertical airflows of an atmospheric thermal (Koch, 2005); Image recognition ability that can identify landmarks from IR (Infra-Red) and visual cameras (Kagabo, 2010; Dennis et. al, 2008); Statistical and mathematical methods estimating the atmospheric boundary layer (Stull, 1988). However, the convection processes of the boundary layer of the Earth atmosphere in real conditions have not been described in detail yet in relation to the on-line condition assessment. Usually they are studied and presented on a larger scale. For example, Stull (1988) provides an overview of the global picture of the nature and the energy in the atmosphere boundary layer. Other studies and reviews focus on the meteorological aspect of the problem. For example, the buildup of convective available potential energy (CAPE) in the free atmosphere has been introduced in meteorology nowadays (Rennó & Ingersoll, 1996).

The studies, a part of which was presented above, do not take into account *current* atmosphere parameters such as temperature and humidity, whereas real-time evaluation of atmosphere and laps rates (dryness, moisture and standard day laps rates) can help obtain a clear picture of an atmosphere boundary layer. Such data can lead to identifying certain dynamic events including updraft airflows. From *any current* situation more information can be extracted like the expected cloud base, which limits the maximum altitude that can be reached using thermal convection, and the expected maximum gain of the thermals. Note that not all of those approaches are convenient for implementation and integration on board of UAV or gliders because they are computationally intensive or slow, or processed off line.

In his book "Understanding the sky" (1992) Dennis Pagen explains in details the events and behaviors of the lower atmosphere related to the soaring flights. "*The air is an ever-changing environment and we must know its ways and wiles in order to fly safely*" (Pagen, 1992). The micro-scale atmosphere in *flyable* conditions is subjected to fast changing conditions since the convective thermal exists for a short period of time (a few minutes). Therefore the purpose of the flying is to use the energy in the atmosphere efficiently *at any moment*.

In this context, the present work proposes a new approach for evaluation of the *micro-scale atmosphere*[1]. It focuses on using piezo-resistive technology that can measure pressure, temperature and relative humidity *fast enough* in order to provide real-time information of the momentum state of the atmosphere in order to obtain a clearer picture of the atmosphere dynamics during the flight. The main issue under consideration here is the thermal convective updraft.

For this purpose several basic algorithms for optimal trajectory of unpowered UAV and piloted gliders for improvement of flight navigation are first evaluated in the paper. Then they are implemented in the specially designed piezo-resistive instrumentation.. This evaluation approach can be applied to other types of dynamics in the atmosphere like convergent lifts, for example. The results of this study can also be useful in meteorology measurement and research.

3. REAL-TIME EVALUATION OF THE ATMOSPHERE BOUNDARY LAYER

3.1. Proposed Methodology

As previously said this research is focused on *real-time modeling* of the environment during a soaring flight. The approach consists of the following steps:

1. Estimation of a vertical profile of the lower troposphere (up to the cloud base) by using piezo-resistive technology;
2. Introduction of a probability distribution (paragraph 3.3, Figure 11) as an *additional variable* in the calculation of the thermal lift vertical speed, based on humidity and temperature measurements;
3. Estimation of flight stability and thermal gain;
4. Identification of the features of a convective thermal based on the measured parameter variations.

The main disadvantage of the existing approaches to recognition of the updraft airlifts is the lack of information regarding the physical state of the atmosphere at *every current moment* since the size and strength of the thermals are influenced by the properties of the lower atmosphere. Thermals are often recognized by the pilot by the presence of visible *cumulus clouds*. But the location of the *convective thermal* is not always possible to be identified and localized by the existence of cumulus clouds. Therefore, the first problem to be resolved is recognition of the main features of the atmosphere that cause change in its behavior.

3.2. Thermal Convection in the Atmosphere Boundary Layer

In order to use thermals as an “energy source” in a soaring flight, it is necessary to define the nature/origin and the shape of the thermal and predict its behavior. Warm air, heated by the sun, rises and acquires the structure of a vortex ring with the upward velocity in the center usually greater than the rate of ascent of the whole thermal. As the ring rises, it is accompanied by an enclosing body, or *shell*, of cooler air, which has been accumulated from its surroundings. Cooler air continuously circulates in closed stream lines around the vortex core resulting in a continuous upward current in the central region of the shell.

There is lack of *real time* measurements in the atmosphere that can be used in the paragliding practice. The provided results on soaring flights are most commonly based on laboratory experiments. This is yet another reason, provoking our interest in measuring atmosphere parameters with light piezo-resistive sensors. Using soaring vehicles (like a paraglider) makes it possible to observe unique *micro events* in the atmosphere first person. The measurements are performed by the first author of the present paper.

Woodward (1959) performed a detailed study of the motions inside and around the *thermal*. We have extended the circulation pattern of a *convective thermal* in the next subsection.

3.3. Laps Rates

Thermodynamics defines the adiabatic lapse rate as:

$$\Gamma_d = \frac{\Delta T}{dz} = \frac{g}{C_p} = 9.8C^{\circ} / km \tag{1}$$

where:

- T is the temperature;
- z the altitude;
- g the gravitational constant;
- C_p the specific heat at constant pressure (Lorenz & Lorenz, 1967).

The current value is an average one, commonly used as a standard value. This expression shows that for adiabatic motion in the vertical, the temperature will fall by ~ $9.8C^{\circ} / km$ in dry atmosphere. Throughout the troposphere, the average lapse rate is about $-6.5C^{\circ} / km$ on average, reflecting both the importance of water vapour condensation (latent heat) and dynamical constraints (small static stability).

The presence of water within the atmosphere complicates the process of convection. Water vapor contains latent heat of vaporization. As mentioned in (Tawan & Kirch, 2016) the release of latent heat is an important source of energy in the development of thunderstorms. Later, the water vapor condenses, releasing heat. Before saturation, the rising air follows the dry adiabatic lapse rate. After saturation, the rising air follows the moist adiabatic lapse rate.

The formula for the moist adiabatic lapse rate (Stull, 2012, p. 102) is given by:

$$\Gamma_w = g \frac{R_{sd} T^2 + H_v r T}{c_{pd} R_{sd} T^2 + H_v^2 r \in} \tag{2}$$

where:

- H_v - is the water heat of vapourization;
- R_{sd} - the specific gas constant of dry air;
- H_v - the dimensionless ratio of the specific gas constant of dry air to the specific gas constant for water vapour;

- ϵ - the dimensionless ratio of the specific gas constant of dry air to the specific gas constant for water vapour;
- e – the water vapour pressure of the saturated air;
- p – the pressure of the saturated air;
- $r = c \in /(p-)$ – the mixing ratio of the mass of water vapour to the mass of dry air.

The formulated temperature laps rates estimate the atmosphere stability as described in paragraph 3.4.

3.4. Atmosphere Stability and Instability

Within the conceptualization of the process how a convective lift (thermal) is created, *stable air* is the air that tends to stay where it is in the vertical dimension. "Stable air occurs when the lapse rate is less than the DALR (Dry Adiabatic Laps Rate) (5.5 °F/ 1000 ft [1 °C/100 m]) and unstable air occurs when the lapse rate is greater than the DALR" (Pagen, 1992, p. 37). Therefore, *convective events* are expected only in unstable atmosphere. Since the higher laps rate is greater than the DALR - stronger updraft/downdraft acceleration gains are expected from the convection (see § 3.6).

3.5. Dew Point

Knowing the dew point (the nearest distance between the green and red line in Figure 1), the theoretical maximum altitude of an atmospheric thermal can be estimated. Depending on the instability of the atmosphere, the presence of condensation and the latent heat continuing to warm the air, the air no longer cools according to the DALR as it continues to rise.

The dew point is calculated by the Magnus formula:

$$D_p\left(T, RH\right) = \frac{\lambda\left(\ln\frac{RH}{100}\right) + \frac{\beta T}{\lambda + T}}{\beta\left(\ln\frac{RH}{100}\right) + \frac{\beta T}{\lambda + T}} \tag{3}$$

where α =*6.112 hPa*, β =*17.62* and λ =*243.12 °C* (Stull,2012, p.92).

Equation (3) is a commonly used approximation, assuming that air pressure remains constant. Flying would be much easier if moisture was not such an influential component found in the at-mosphere. Moisture in the air creates more hazards during the flight than any other weather phe-nomenon. Water in the atmosphere is measured by the relative humidity and dew point accom-panied by a temperature-dew point spread. Knowing the conditions during which water changes state also helps pilots to avoid moisture-related problems during flight. Note that all of the varia-bles in the Magnus formula can be provided from the piezo-resistive sensor. This means that the dew point can be calculated in a real time.

3.6. Thermal Visualization

The micro-scale atmosphere, especially in an *unstable condition,* is changing fast its position. According to our model an estimated atmosphere profile of the lower troposphere is obtained by integrating equations (2) and (3) by Δp.

The experimental variogram[2] from the sample data is computed as in (Bohling, 2005):

$$\gamma\left(h\right)=\frac{1}{2n\left(h\right)}\sum_{i=1}^{n\left(h\right)}\left\{z\left(x_i\right)-z\left(x_i+h\right)\right\}^2 \tag{4}$$

where:

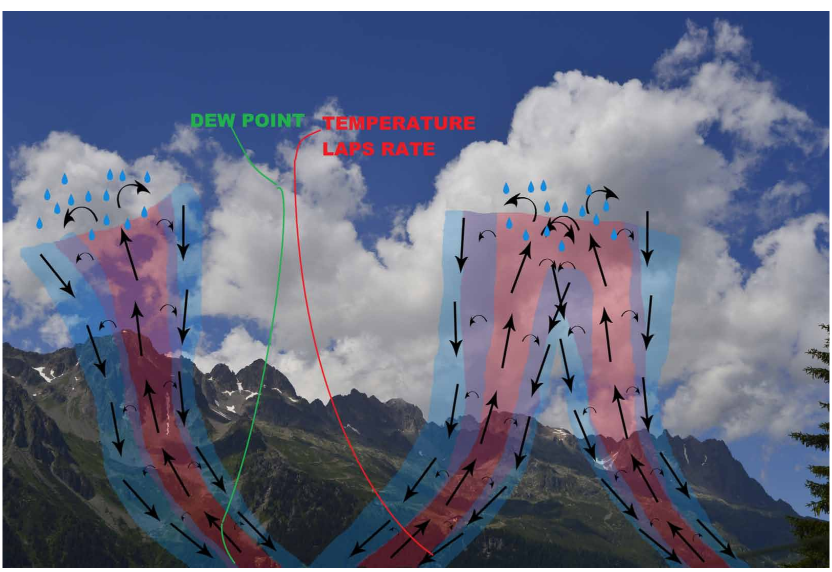
- $z\left(x_i\right)$ is the observed value of z at vertical location x_i separated by distance h;
- n is the number of sample pairs.

Figure 1 gives visualization of a diagram of the thermal from the ground to the cumulus cloud (dew point).

3.7. Updraft Atmosphere Thermal Velocity

In soaring, the thermal identification method for estimation of the updraft velocity of the thermal is based on the vehicle energy change rate and the vehicle speed polar. The energy gain from the atmospheric thermal is in the form of altitude gain caused by the updraft velocity. The vertical velocity component of the atmospheric thermal, acting on the aircraft, will cause it to ascend. The speed, with which the

Figure 1. Thermal activity at a mountain ridge



thermal rises, is given relative to the atmosphere and the absolute vertical velocity of the air at any point in the thermal in still air (Cone, 1964). A mathematical model of updraft acceleration is described in (Akhtar, 2008). However, this approach can only be used for identifying a thermal when the aircraft is already in it. *Our approach adds the precise measurements of humidity, temperature and pressure to the updraft acceleration model in order to bridge the time gap between the atmospheric thermal identification and the soaring in order to provide relevant online information to the pilot or the measurement system.*

4. FIELD STUDY OF THE ATMOSPHERE BOUNDARY LAYERS

4.1. Measuring the Micro-Scaled Atmosphere

In the present work, we have in order to measure the micro-scaled atmosphere a *measurement system for online evaluation* of the convection events in the atmosphere during a soaring flight was designed. It consists of the following hardware components:

1. Launchpad TI MSP430FR5994 and SD Card development kit (Texas Instruments);
2. Digital sensor BME280 (Bosh Sensortec);
3. Standard 4xAAA batteries supplying the system with 3.3V through microchip MCP series LDO (low drop out regulator);
4. Quectel L86 GPS Module.

The following software modules have been implemented in the measurement system:

1. Texas instrument library for SD Card recording;
2. Bosh Sensortec library for interfacing the BME280 sensor.

The main function of the assembled module is to record the measured humidity, temperature and pressure. Low pass filters, appropriately configured for outdoor navigation, are used following the recommendations in the Bosh BME280 datasheet. During the experimental flights the sample rate of the sensor is set to 30 Hz (1 sample measurement per 33.(3) milliseconds).

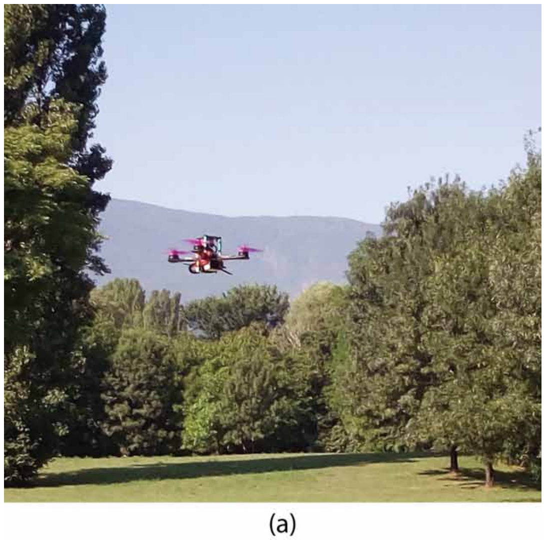
4.2. Experimental Setup

Several measurement sessions for obtaining real life data were performed (Figure 2). The quadcopter drone performed 500 meters vertical ascending and descending, respectively. Two of the flights tried to reach the cloud base. The paraglider flights are performed in unstable conditions (paragraph 3.4).

4.3. Experimental Results and Discussion

Figure 3 and 4 visualize the flight profile of one of the performed soaring flight tests.

Figure 2. Experimental flights: (a) Quadcopter drone platform; (b) Piloted paraglider



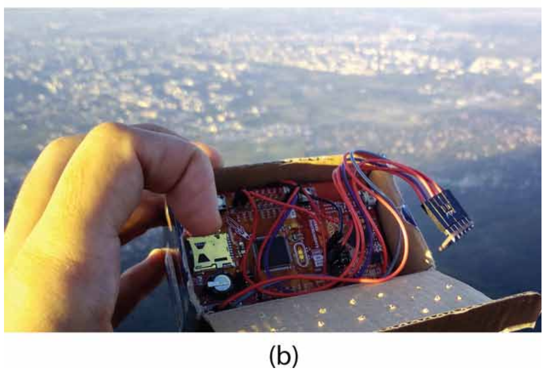


Figure 3. Soaring flight test profile of pressure and temperature

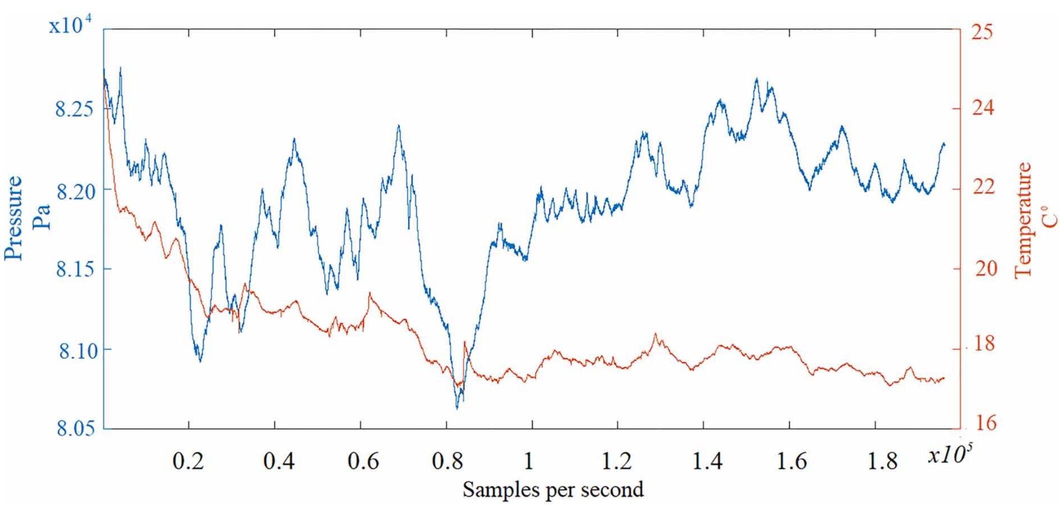


Figure 4. Soaring flight test profile of relative humidity %

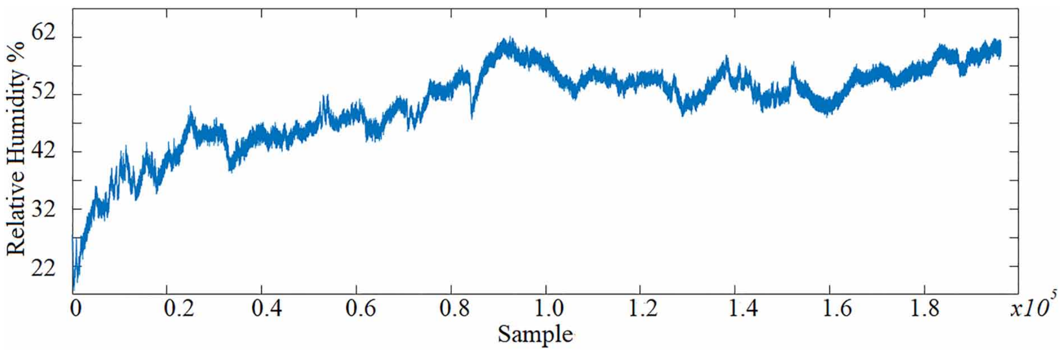


Figure 3 presents the temperature and the pressure along the vertical axis and the samples of sensor data along the horizontal axis. As for Figure 4 presents along the vertical axis the humidity.

Figure 5 visualizes the trajectory in a rectangular coordinate system, correlated to Figure 3 and Figure 4.

In Figure 5 along the vertical axis is the altitude and the horizontal axes are the geographical latitude and the longitude. Figure 6 presents in 3 dimensions the respective trajectory from Figure 5 transferred in “Google Earth” version Pro. 7.3.1 in the World Geodetic System (WGS) (1984).

The next figures visualize the observed parameters (temperature, pressure and relative humidity). The main thermodynamics parameters of the boundary layer (the laps rates and the dew point*) are evaluated at any moment* of the flight in real time by our multi-sensory system. In this way, the atmosphere processes can be measured with much more detailed resolution.

Figure 5. GPS Trajectory of the paraglider flight in rectangular coordinate system

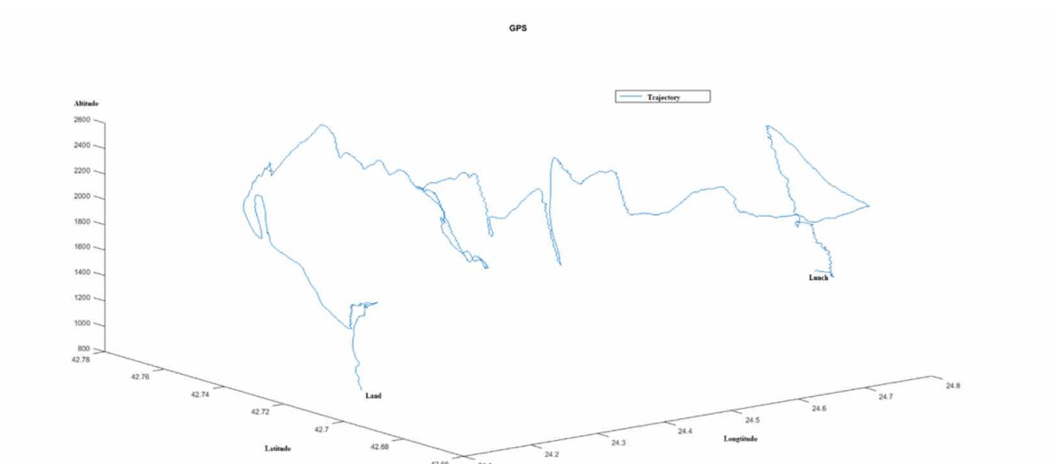
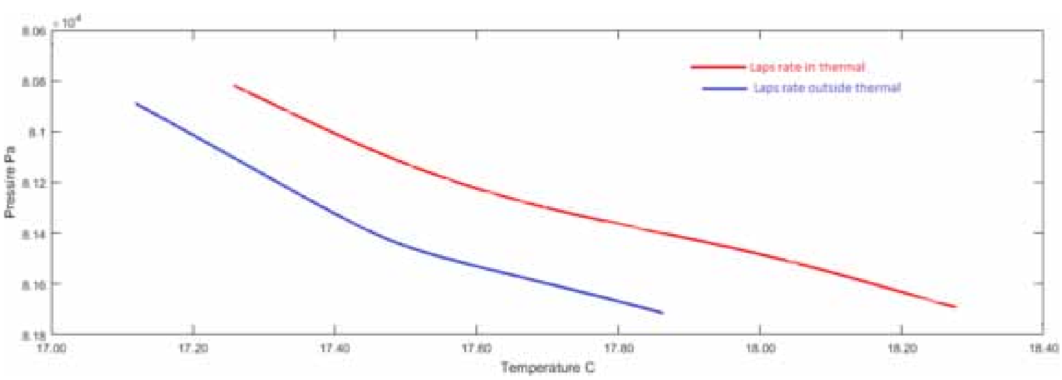


Figure 6. GPS Trajectory of the paraglider flight translated in WGS coordinate system

Figure 7 presents the momentum laps rates at the same pressure altitude during soaring in up draft flow (thermal) and in relatively stable conditions according to (4). The laps rates in Figure 7 are approximately 1.213° C in the convective thermal (red line) and 1.154° C outside the convective thermal (blue line). This confirms that the piezo-resistive sensor is capable of measuring data (pressure, humidity and temperature) thus providing altitude profile information. It clearly shows that there are *different temperature laps rates inside of the convection core and outside it*. Furthermore, it makes evident the different temperature inside and outside the core in the real atmosphere. Adding the measured relative humidity allows calculating the dew point (3) and the pressure (altitude) of the cloud base *with much higher precision* than with the offline or forecast data, since usually the cloud base is calculated based on a forecast models and algorithms in a resolution up to 50 km.

In theory, the thermal convection can be assumed as adiabatic process, as mentioned in the introduction. However, the differences in the laps rates inside and outside the thermal, and the difference of the measured temperature (ΔT) at around (0.2° – 0.6°) C (see Figure 5) demonstrate that there is heat exchange *at the border*

Figure 7. Momentum laps rate in and outside convective thermal



of a convection thermal. For example, in 6 out of 10 cases of thermal entering with a paraglider temperature increase is observed before the climbing starts (Figure 8).

By analogy, after exiting the thermal, as sinking begins the temperature rate stays constant for a while (Figure 9).

The vertical speed and temperature during entering a *convective thermal core* is clearly observed. It confirms the circulation pattern of Woodward (1957) and the vortex ring system of Cone (1964). It also indicates some temperature fluctuations (heat exchange) and strong turbulent air on the border of the core, obtained by the online measurement during the soaring flight.

The updraft velocity in the thermal is calculated by:

$$V' = V_c^{'} - V_d^{r} \tag{5}$$

Figure 8. Temperature rate increasing before entering in convective thermal

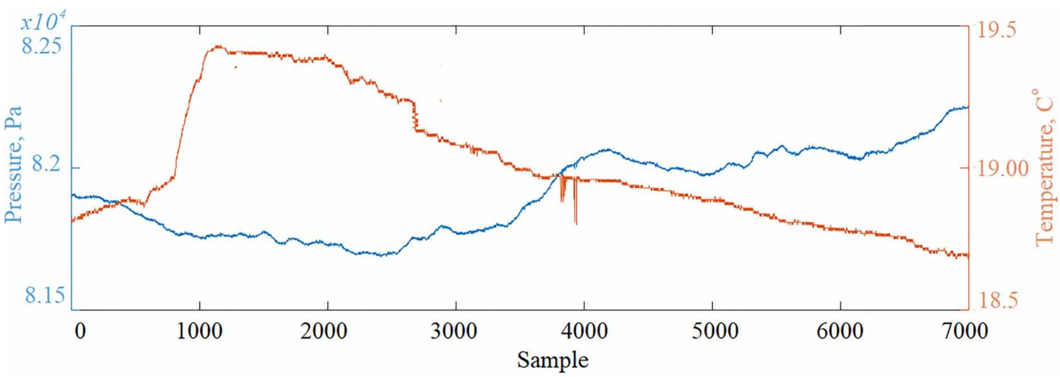
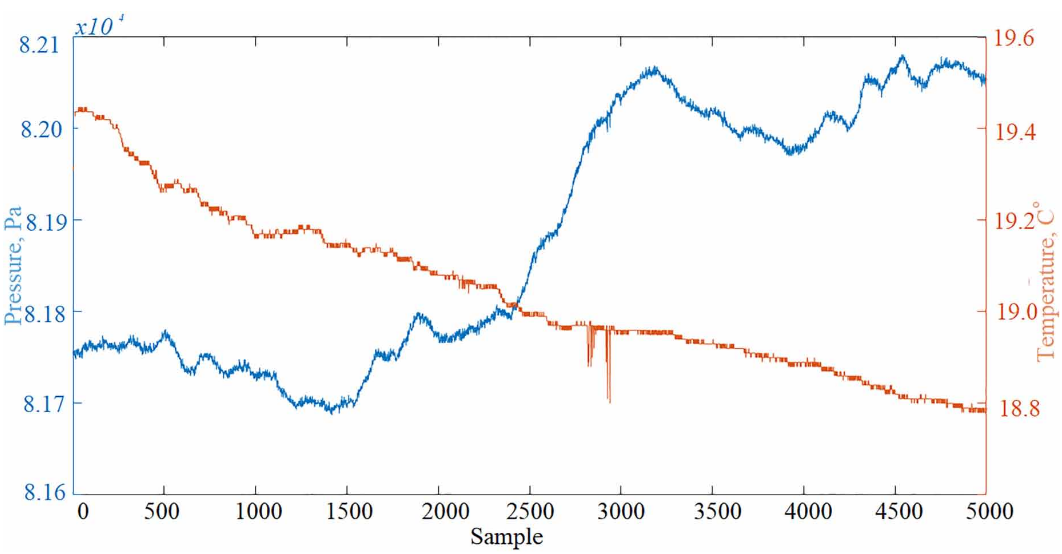


Figure 9. Temperature rate decreasing before exiting the convective thermal



where:

- V_c is the *climb rate* of the glider in the certain thermal;
- $V_d^{'}$ the *sink rate* of the glider at a given radius turn.

The probability distribution of ΔT and the vertical velocity of the convective thermal (lift strength) are given in Figure 10. (temperature laps rate along the vertical axis and vertical velocity along the horizontal axis). The correlation between those parameters is evident from the figure and it is almost 0.7.

Figure 11 presents the maximal vertical velocity along the vertical axis and the temperature rate along the horizontal axis. The red line is the function of the maximal measured vertical velocity defined by the temperature rate. The linear relation of these parameters and the respective correlation are clearly visible.

The main empirical result of the presented current work is: By using widely available nowadays sensors we are *capable of detecting small temperature fluctuations in a fast manner for atmosphere dynamics prediction by the pilot or the multi-sensory system.*

During the experiments some disadvantages of the implemented approach have been observed, such as: operational limitation of the humidity measurements due to sensor design (temperature operation limits); inappropriate sensor location, need for additional isolation from sun heating and direct flow venting, due of the noise during parameter's measuring.

4.4. Future Work

Pressure sensors data (measuring altitude, vertical velocity) and temperature measurements can be fused via a two state Kalman filter, with one state being the pressure and the other one being the temperature bias in two main steps – *state* update and *Kalman* update (e.g. Titterton, 2004). The state update is used at every time

Figure 10. Probability distribution between the temperature lapse rate and the vertical velocity (lift strength)

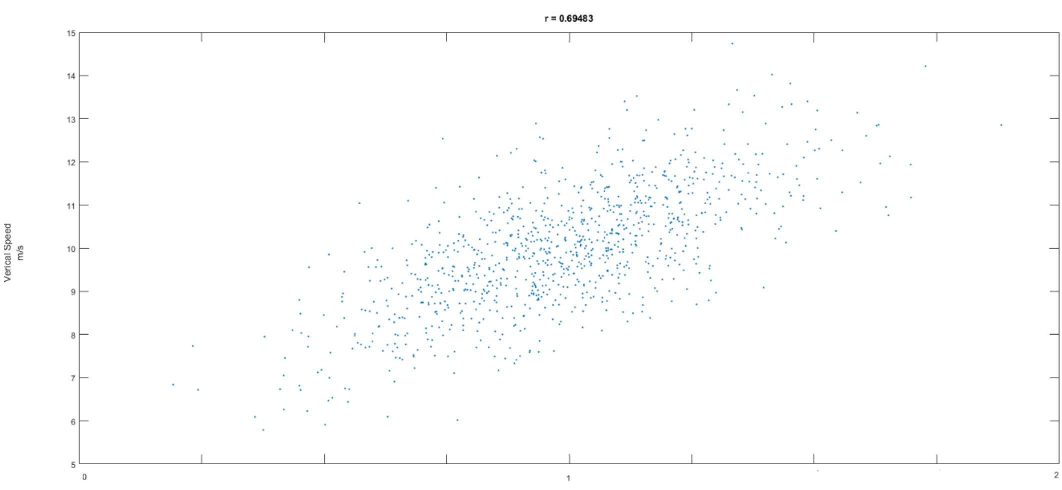
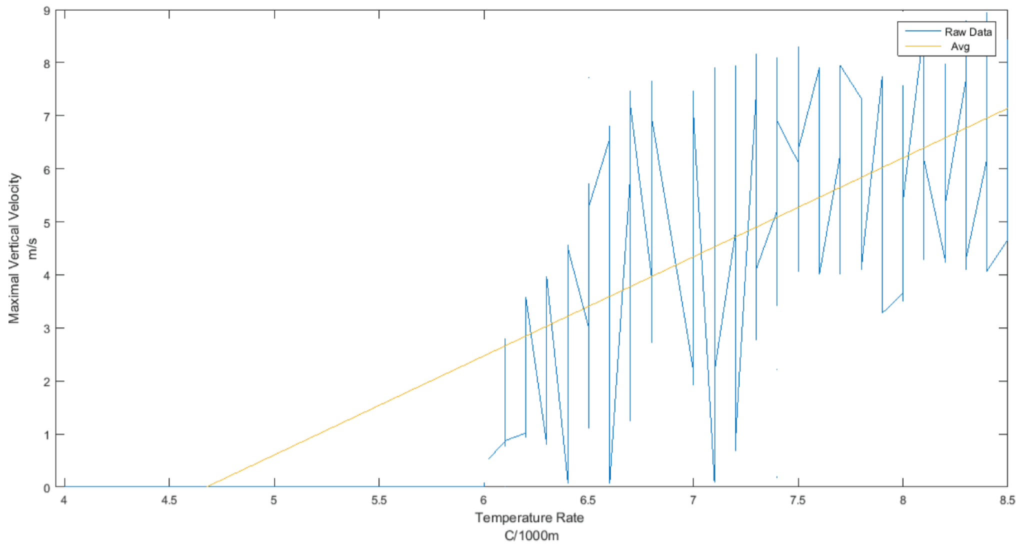


Figure 11. The function of the maximal measured vertical velocity defined by the temperature rate in altitude



step (*dt*) – discrete time - with a biased temperature measurement by the user of the module. The filter will track the bias. Thus the Kalman update can be used when a new pressure measurement is performed. The covariance matrix P of the filter is updated at every time step (*dt*) thus allowing to determine how accurately the pressure sensor is tracking the actual state.

Consequently, more test flights and data are necessary in order to obtain more information on the actual dependencies between the measured data and the calculated state of the atmosphere. It is also important that the experiments are accomplished in different atmosphere conditions. Thus, the following parameters and measurements will be systematized in the future:

- Atmosphere temperature laps rate;
- Moist adiabatic laps rate;
- Altitude of the entering/exiting the convective thermal;
- Temperature and humidity difference inside the convective thermal relative to the average surrounding atmosphere;
- Temperature bias by the pressure (if available);
- Vertical speed of the convective thermal.

The stated above parameters can be computed in a correlation matrix, which will represent the dependence between all the variables at once thus providing more reliable information. Also, there is a possibility to include more parameters to model the atmosphere thermals, like:

- Adding complementary coefficients in the barometric vertical measurements;
- Extending the updrafts/downdrafts detection algorithms.

Finally, the proposed approach can be combined with optimal trajectory algorithms for better control of the trajectory and duration of the soaring flight.

5. CONCLUSION

The proposed modeling approach, provides a detailed representation of the atmosphere boundary layer dynamics based on real-time data measurements. The main advantage of the proposed approach is in its more *precise calculation* of the expected rates of thermal activity in the boundary layer. The presented empirical results support the expectation that the nowadays produced piezo-resistive sensors can perform accurate and fast measurements during the flight thus allowing to predict emerging thermals in online manner. The results reflect two main aspects of the model: the first one is related to micro-scale atmosphere measurements and evaluation; the second one is related to atmosphere thermal convection identification. The temperature rate identification allows detecting a possible approaching of a thermal by the paraglider, which is crucial for the pilot safety.

As previously said, future work will consider the integration of more parameters in the proposed approach such as: wind speed, wind direction, precise position determination using internal and satellite global navigation systems. This will allow full 3-dimensional (3D) modeling of the convection events in the atmosphere boundary levels.

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ENDNOTES

[1] Micro-scale atmosphere is defined here to focus on fast and dynamic processes that can influence the soaring trajectory but are not included in the existing off-line models in the literature.

[2] The values of the semivariance $\gamma(h)$, plotted against h is called variogram.

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