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SOARING FLIGHT TRAJECTORY OPTIMIZATION IN CONVECTIVE THERMALS

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Abstract: *The thermal soaring technique involves extraction of energy from the convective updrafts in the atmosphere. The effective soaring in convective thermals requires a dynamic maneuvering. In those maneuvers, the kinetic energy is converted into potential energy by gaining altitude and by most cases reducing airspeed. Then initial values of altitude and speed are gained by losing the altitude, but the result of this process is the horizontal distance. The key problem associated with optimal trajectory of soaring in a convective thermal is actually the determination and evaluation of the thermal. The innovative approach in this work is the real time modeling instead of the implementation of theoretical models. The real time data, which are actually the inputs of the modeling, are gained from Micro electro-mechanical sensors and a GPSS (Global Positioning System Sensor). Next, this real time model will be applied on a flight control model in order to demonstrate the result soaring trajectory in the convective thermal. 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. Several paraglider and quad-copter flights are performed in order to obtain required data and demonstrate the developed real time modeling.*

Key words: *flying machine, real time modeling*, sensor.

1. INTRODUCTION

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There are different forms of energy in the atmosphere boundary layer. Some forms are stronger, but less predictable than others. Dynamical forms of energy can be found in: i). ridges (and orographic lift, where the slopes of hills and mountains deflect wind); ii). atmospheric thermals (uneven heating of the ground, which produces buoyant instabilities); iii). waves (long period oscillations of the atmosphere, which occur in the lee of large mountain ranges). In recent years also a theoretical and experimental investigation of energy extraction from atmospheric turbulence [1] is performed. Of all these, the atmospheric thermals are the most commonly used form for soaring flights, the reason being that atmospheric thermals have an abundant occurrence in all types of terrains, in both hilly and flat terrains.

In order to use thermals as an “energy source” in a soaring flight we need to know in details it’s nature and shapes and behavior. A literature search could be summarized in two branches. Researches and numerical simulations have been reproduced in laboratory by Morton et al. (1956), Scorer (1957), Woodward (1959)[3], Turner (1963), S´anchez et al. (1989) and Johari (1992).

On the other hand, we have empirical studies described in several soaring flight books stongly related to the type and characteristics of the flying machine. It is obvious that soaring pilots are the largest group of “users” of convective thermals and it could be mistake if we doesn't consider their experience.

In the first case we are lacking of a “real life” production of a convective thermal. Where in the second case there are described many “best practices” situations which are hardly for designing a model or algorithm for trajectory optimization.

A further research regrading an optimal trajectory estimation of an unpowered aircraft provides two main approaches. The first one, commonly used in autonomous soaring algorithms, uses a statistical methods to determine the size of an thermal.

And based on that, it adjusts the optimal flying configurations and turn radios of the vehicles. The second one, mainly used in soaring flight instrumentations is so called “Thermal Ball” – the point of the strongest lift. The pilot is always trying to circling around this point, while trying to keep maximum positive vertical speed. [4]

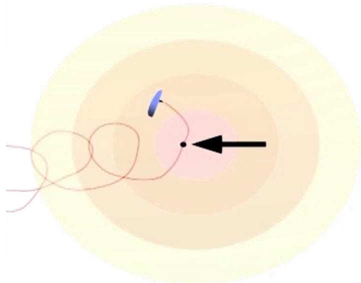

Figure 3

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In this work, a new method is proposed that combines both approaches for trajectory optimization of a flying vehicle in convective thermal. Real-time thermal pattern will be determined and based on aerodynamics and maneuvering characteristics of the glider an optimization of the soaring trajectory will be estimated.

1. THERMAL MODEL

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A thermal is a collection of air rising trough the general mass because it is lighter than its surroundings. Warm air, resulting from the sun's heating, 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 according to Cone [2]. He closely approximates a free thermal to a buoyant vortex ring system in which the ring to core radius ratio (R/a) is less than 10. As the ring rises, it is accompanied by an enclosing body, or shell, of cooler air which it has gathered from its surroundings. Figure 1 illustrates the internal structure of such a thermal. 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. The average speed with which the thermal rises relative to the atmosphere is given by:

$$V' = \frac{r}{4\Gamma R}\left(ln\frac{8R}{a} - \frac{1}{4}\right) \quad (1)$$

Where the entire velocity field can be specified if the circulation –Γ , the ring radius - R, and core radius – a are given

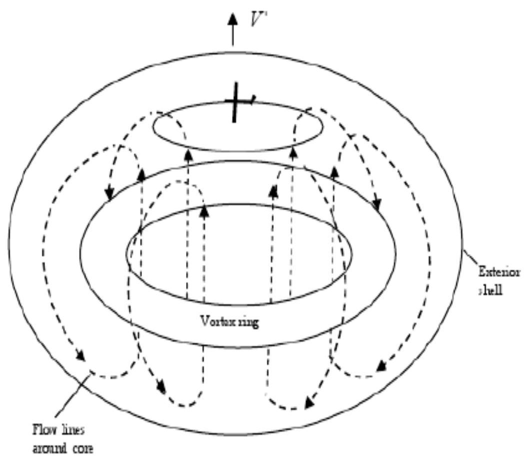

Figure 1 Thermal Core [2]

Woodward performed the most detailed study of the motions inside and around the thermal. Her results have provided us with the classic circulation pattern of a laboratory thermal. Her results have provided us with the classic circulation pattern of a laboratory thermal; the velocity patterns are shown in Figure 2. It is obvious that classed to the center of the thermal the updraft is bigger, also shown on Woodward's Figure 2.

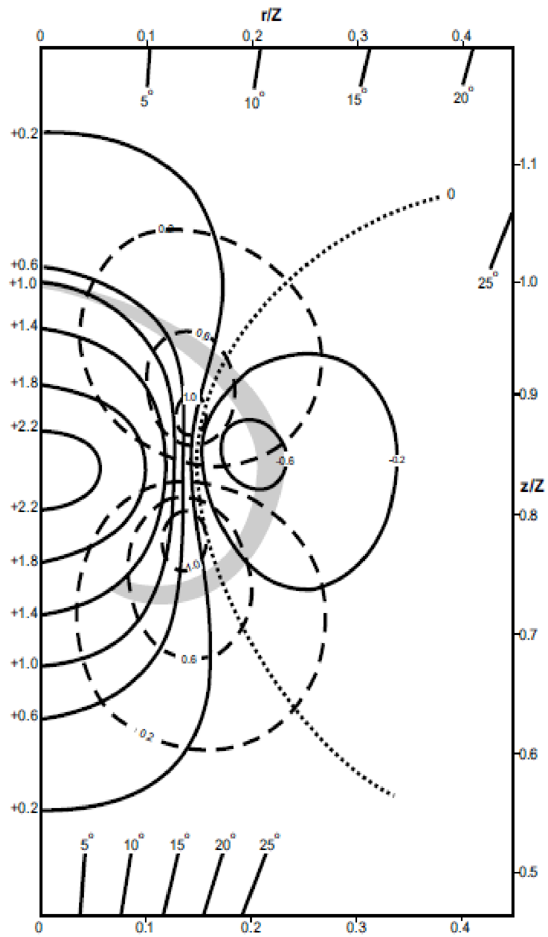

Figure 2 Circulation pattern of a laboratory thermal [3]

As per Woodward, the velocity in the core of thermal are close to a linear function.

1. GLIDING PERFORMANCE

A typical cross-country flight pattern includes circling in a thermal. This is one of the most important part of the soaring flight.

There are different types of gliders, but there flight performance and characteristics. The difference are in speed ranges and if available in the different flight configurations. For examples some sail planes have airbrakes, flaps or tail trim, also some of them carry ballast weight in a water tank. However, the polar curves shapes of all of them are quite similar.

If the air is rising we displace the origin down by an amount equal to the rate at which the air is going up, and then draw a tangent from that point to the polar curve. This gives a valid speed only if we plan to fly straight through the lift. If we plan to circle in the lift, other factors determine the speed that will optimize our climb rate.

In a turn at constant speed, the Angle of attack must be increased to furnish the extra lift necessary to overcome the centrifugal force and inertia opposing the turn. As the bank angle increases, Angle of attack must also increase to provide the required lift. The result of increasing the

AOA is a stall when the critical Angle of attack is exceeded in a turn.

Rate of turn refers to the amount of time it takes for a glider to turn a specified number of degrees. If flown at the same airspeed and angle of bank, every glider turns at the same rate. If airspeed increases and the angle of bank remains the same, the rate of turn decreases. Conversely, a constant airspeed coupled with an angle of bank increase results in a higher rate of turn.
The amount of horizontal distance an aircraft uses to complete a turn is referred to as the radius of turn. The radius of turn at any given bank angle varies directly with the square of the airspeed. Therefore, if the airspeed of the glider were doubled, the radius of the turn would be four times greater. Although the radius of turn is also dependent on a glider's airspeed and angle of bank, the relationship is the opposite of rate of turn. As the glider's airspeed is increased with the angle of bank held constant, the radius of turn increases. On the other hand, if the angle of bank increases and the airspeed remains the same, the radius of turn is decreased. When flying in thermals, the radius of turn is an important factor as it helps to gain the maximum altitude. A smaller turn radius enables a glider to fly closer to the fastest rising core of the thermal and gain altitude more quickly. It is important that rudder and aileron inputs are coordinated during a turn so maximum glider performance can be maintained.

The sink angle of the trajectory $\emptyset$ of a glider in a roll turn could be estimated by:

$$sin\emptyset = -\frac{n_y}{K} \quad (2)$$

Where, K is the lift/drag ration and:

$$n_y = \frac{1}{cos\gamma} \quad (3)$$

Where, γ is the roll angle.

In the paraglider, where the most of the flight tests are performed, the angle of attack and the speed are harder to control, because controlling of the glider represents using left and right airbrakes and weight shifting. The polar speed curve of the paraglider performing the flight tests and measurements are shown on Figure 4.
Unlike other flying machines paragliders are not rigid, they are flexible fabric structures. The performance values derived from extensive computer simulation only work for the computer model. The paraglider deforms in the air and this alters the aerodynamics. The most sophisticated simulation can only produce relative predictions. Absolute results cannot be regarded as completely sound. Total drag varies significantly as a function of harness, sitting position, clothes, helmet or arm position. Glide performance figures taken from life are only valid for the heights, humidities and temperatures in which they were flown. This is the reason the shown flight characteristic in this work are obtained from the performed flight tests.

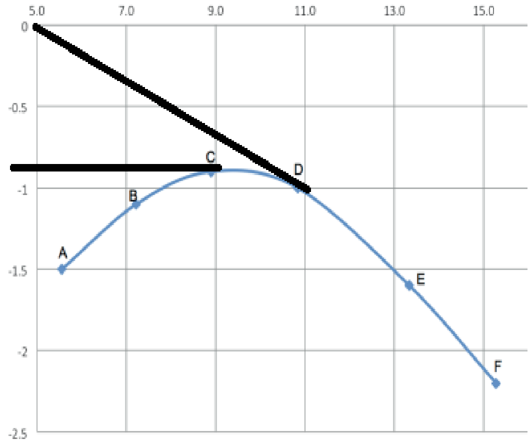

Figure 3 Paraglider polar curves [6]

Point	A	B	C	D	E	F
Speed Km/h	20	26	32	39	48	55
Speed control	Min speed	50% breaks	30% breaks	trim	50% speed bar	100% speed bar

Table 1 [6]

On Figure 3 are shown the minimum sink rate speed and also the best lift/drag point using a tangent line from the center of the graph to the curve.

In general, as in a horizontal flight, the best performance configuration. The primary assumption is that the glider airspeed is maintained at minimum sink rate airspeed so as to stay longer in the thermal and achieve higher altitude gain.

The most common trajectory in convective thermal is based on the minimum sink rate and averaging table of sizes relative to the average "strength" (updraft velocity) of the thermal.

On figure 4 is shown a turn sink rate curve of the used paraglider.

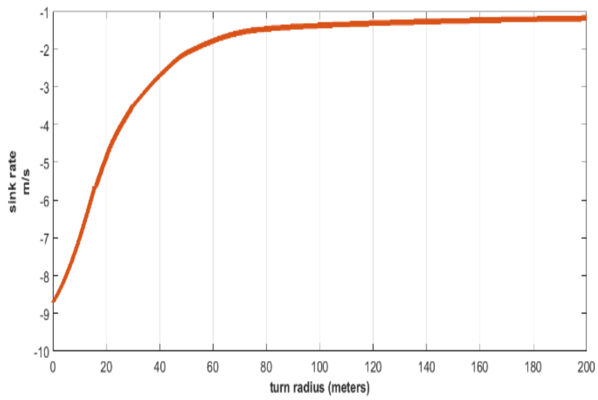

Figure 4. Turn sink rate curve

The sink rate in a turn is [7]:

$$v_d = -usin\gamma$$

Where u is the true air speed and γ is the roll angle.

Unfortunately based on the performed flight tests, it is summarized that the size and the strength of the updrafts are no so relevant. A reason for this could be the source or so called thermal triggers as described D. Peganen – Lee side thermals, surface types (urban areas, rocks, forests, sands, wet fields and other terrain sources exposed to direct sun heat).[3] On the other side the boundary layer laps rates that defines the instability of atmosphere and other physical state of air as humidity could affect the lock of the convective updrafts. For example a wide but weak thermals are observed over a flat terrains and small but strong ones are observed over mountain ridges. This in combination whit the fixed roll angle for circling in the updraft could lead to missed thermal core or using inefficient roll angle. For example, what if increase or decrease the turn radios if it summed up leads to better climb rate?

3. MEASURING SYSTEM

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A measurement system is developed to perform the flight test, consisting of the following hardware components: *i).* Launchpad TI MSP430FR5994 and SD Card development kit (Texas Instruments); *ii).* Digital sensor BME280 (Bosh Sensortec); *iii)* Global Positioning Sensor (GPS) Quectel L86; LSM9DS microelectromechanical measurement sensor (inertials and accelerometers); *iv).* Lithium-Polymer 3.3V battery trough microchip MCP series LDO (low drop out regulator).

The following software modules ~~are~~ have been implemented in the measurement system in our lab: *i).* Texas instrument library for SD Card recording; *ii).* Bosh Sensortec library for interfacing the BME280 sensor. The main function of the assembled module is to record the measured data. Low pass filters, appropriately configured for outdoor navigation, are used. During the experimental flights the sample rates of the sensors are set to 30 Hz for the BME280 sensor, 1Hz for the GPS and 60HZ for the inertial navigation.

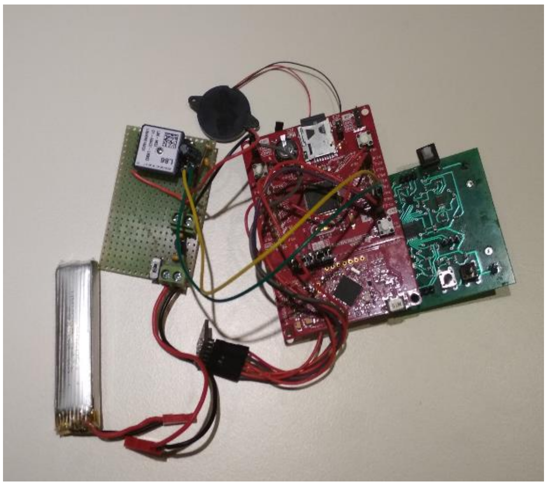

Figure 5 The measurement system

4. TRAJECTORY OPTIMISATION

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The updraft velocity in the thermal would be:

$$V' = V_c' - V_d^r \quad (4)$$

Where V_c is the climb rate of the glider in the certain thermal and V_d' is the sink rate of the glider at given turn radius. It is obvious for the optimal radius turn we are requiring the maximum V_c^i:

$$V_c^i = V_d^r + V^i \quad (5)$$

The identification of a thermal is the first or climb detected, or additional method could be used.

After the thermal is centered the rate of the increasing the vertical speed to the center is:

$$v_{tr} = \frac{V_c^i}{R - R_\gamma} \quad (6)$$

Where R_γ is the current radius of turn. Based on this rate and the turn sink rate curve on figure 4 we could chose the right radius.

At Figure 5 is visualized an trajectory of a paraglider flight in dynamic thermaling using the circling technique. The trajectory is visualized using "Google Earth" version Pro. 7.3.1. The gained altitude is 955 meters in total and the climb is separate to 3 parts:

- Turn radius – 34 meters
- Turn radius – 48 meters
- Turn radius – 60 meters

This particular test flight is performed in Bulgaria at the following coordinates: 42 36' 57" N 24 57' 15"E. This is a part of the flight.

Figure 6 Trajectory of dynamic thermaling

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On figure 7 is shown the vertical speed of the glider during the climbing.

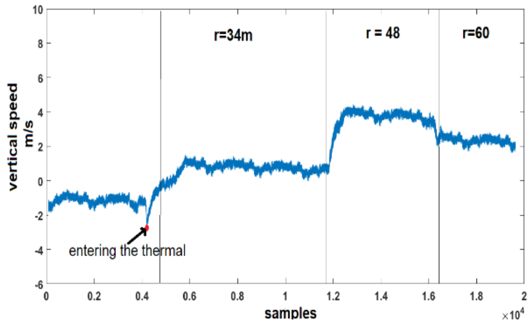

Figure 7 Climb rates in dynamic thermaling

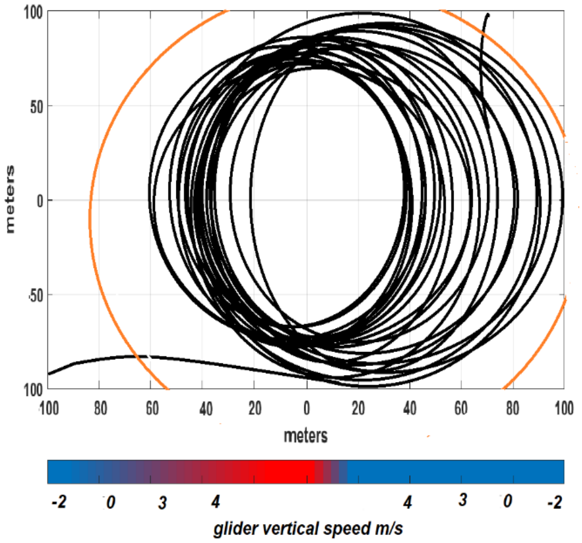

Figure 8 Trajectory in horizontal projection

On figure 8 is visualized the trajectory in horizontal projection.

The results are summarized in table 2:

Turn radius	Avg.Climb speed	Gained altitude
34 m	2 m/s	245 m
48 m	4 m/s	551 m
60 m	3 m/s	159 m

5. CONCLUSIONS

The stated results provide an method to improve a flexible turn radius in convective thermal. This work explores a strategy might employ to maximize climb rate in a thermal. Also it shows that different turns could be performed and different results are achieved depend of the real time conditions. Further this method could be beneficial in decision algorithm for using a convective lift. The main advantage of the proposed approach is:

- in providing faster climb rate;
- in evaluating the vertical speed in a convective thermal;
- in possibility to use narrow convective thermals.

Future work will consider the integration of more parameters in the proposed approach such as: wind speed, wind direction, and precise position determination using internal references sensors. Additional fight test will be performed on remotely controlled soaring platform.

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