Unmanned Aerial Vehicles as an Alternative to Traditional Snow Profiling

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***Abstract*—Avalanche prediction needs a variety of methods and tools. While modelling snow conditions became more popular in recent years, field observations still are essential for proper assessment. This article presents a systematic literature review of methods and tools currently used by avalanche experts. Additionaly the methods for developing an octocopter capable of handling a snow profiling device and the option for autonomous operation are pointed out. This approach for remote snow stratigraphy analysis is suggested as an alternative to manned snow cover analysis in the field.**

***Index Terms*—avalanche prediction, snowpack, UAV.**

I. Introduction

DESPITE rapid development in the field of avalanche forecasting the estimated annual fatalities related to backcountry skiing in Austria show a slight increase [1].

Referring to Schweizer et al. [2], current avalanche forecasting relies on meteorological observations and forecasts combined with in-situ snow pack evaluation and documentation of avalanche incidents. As stated by Morin et al. [3] the snow stratigraphy is a deciding factor in the probability of avalanche release. Differences in the microstructure like grain size and hardness often lead to structural weaknesses. A layer of surface hoar, facetted crystals or depth hoar forming a so called weak layer beneath a slab of snow is the most common instance of such a weakness.

When used in research environment, one-dimensional snowpack models are able to provide reliable nowcasts and forecasts on snow structure and diagnose snowpack stability. They combine meteorological information and data from automated weatherstations to emulate nowcast and forecast of snowpack conditions [3].
In real time application on the other hand, free simulations of snowpack stratigraphy accumulate errors and subsequently deviate from field observations. Using models to interpolate field observations on the other hand provides continuous information on snowpack conditions while reducing errors compared to free simulations. [3] [4]

Due to its importance regarding avalanche hazard prediction and popularity among experts [5] this article aims to give an overview on methods and tools used for in-situ snow pack evaluation. Finally a new concept of performing snow layer analysis with the help of an Unmanned Aerial Vehicle (UAV) is presented.

II. Methods

A systematic literature research was conducted to gather information about currently used methods for in-situ snow pack evaluation. Additionaly, the development of a drone capable of performing enable snow pack evaluation is described.

A. Systematic literature research

1) Inclusion criterion: Only studies providing information about methodology and tools used to evaluate snowpack were included in this article. No subject areas were excluded. Only studies written in English were included. Due to rapid technical advancements and climate change considerations, the publication date was limited to 2016-2021.

2) Literature identification: The database ScienceDirect was searched to ensure scientifically sound results while keeping a broad variety of disciplines available. The literature search was initiated with the keywords ”snow profile” and ”avalanche forecast” combined with an AND boolean operator. Due to the high specificity of the keywords there were less than ten results obtained. In order to gather more results and not exclude relevant articles due to linguistic choice, analogous wording for ”snow profile” as well as ”avalanche forecast” was added to the search term. A few iterations of doing so resulted in 31 articles. The final search term used was
(”snowpack test” OR ”snow cover analysis” OR ”snow profile” OR ”stratigraphy” OR ”stability test”) AND (”avalanche hazard” OR ”avalanche risk” OR ”avalanche prediction” OR ”avalanche forecast” OR ”avalanche warning”).
After thorough screening of the results and excluding publications focused on snowpack modelling, a total of 11 articles were found to be related to the methodology and tools used to evaluate snowpack. This includes three publications categorized as secondary literature.
Secondary literature used in the analysed papers was included when it had an essential impact on understanding context or if it was referenced for a more detailed elaboration on snow profiling methods. Publication date was not limited for secondary literature since citation in primary literature is good measure for relevancy.

3) Analysis and Synthesis: The chosen publications were screened for specific methods and tools used in snowpack analysis. Findings were synthesized and resulted in a total number of eight methods and tools used.

B. Development of a snow profiling UAV

The concept of snow cover analysis with a drone consists of a Snow Profiling Device (SPD) and a drone that can position it, drop it, and pick it up again. Main components of such a concept are the lifting body, the payload interface, and the controls of the UAV. Using rapid protopying, a payload interface similar to the winch used by Stefano et al. [6] was developed. To ensure best performance, an online market survey on remote controlled (RC) winches and a cost utility analysis based on Kühnapfel [7] was performed. For appropriate sizing of the lifting body, component selection according to Biczyski et al. [8] using a Matlab model was done. Validation was carried out with eCalc, a tool proven to be accurate and reliable for multicopter sizing [9]. To navigate the drone, a control system tailored to the requirements was selected.

III. Results

A. Current methods and tools used for snow layer analysis

1) Method according to Fierz et al.: With this method, the snow stratigraphy is described by parameters analysed in specific steps. A snowpit from snow surface up until ground contact is digged. This should result in a vertical observation plane in parallel to the fall line. The exposed snowpack is distinguished into different homogeneous layers. Each layer is described by the attributes snow hardness, liquid water content, grain shape, grain size and snow density.

Snow hardness is either determined by a Swiss Ramsonde measurement or the hand hardness test. With the Swiss Ramsonde the snow hardness is represented by the ram resistance in Newtons. The hand hardness test is performed by driving different objects into a snow layer with an estimated force of 10 N. The biggest object able to penetrate into the snow layer determines the hand hardness index and correlating ram resistance as shown in Table I. The observations are largely dependent on the actual objects and force used by the person performing the hand hardness test. Therefore this way of determining snow hardness is rather subjective and lacks repeatability and reproducibility. [4][10][11]

TABLE I
Snow hardness

Snow hardness	Hand hardness index	Object	Ram resistance
very soft	1	fist	20
soft	2	4 fingers	100
medium	3	1 finger	250
hard	4	sharpened pencil	500
very hard	5	knife blade	1000
ice	6	-	>1200

based on [10], page 6

For estimating the liquid water content of the snow layers a variety of methods can be applied. Different versions of calorimetry, the dilution method and dielectric measurements represent standardized methods using tools. A more subjective method is performed by visual inspection and compression of snow with gloves. The differences in visual appearance and behaviour when compressed is documented. Based on Table II, approximations regarding the liquid water content are performed. [4][10]

Grain shape of each snow layer is determined by visual inspection with a minimum magnification of 8x up to using a microscope. Observations are done on a crystal card and compared to the available morpholocical classes of shape types. Documentation is done by using standardized symbols or an abbreviation code. [4][10]

The grain size of a given layer is defined by the average grain size inside it. The size of an individual grain most often is determined by the maximum two dimensional length. More sophisticated sizing methodologies include sieving, stereology and determining the optical equivalent grain size. The latter better represents the electromagnetic properties of the snowpack but also requires more resources. Snow density of an individual snow layer is measured by weighing a specific snow volume extracted with a core drill. A last parameter important in snowpack analysis is the snow temperature. In contrast to the other attributes snow temperature is not determined dependent on individual snow layers. It is documented in a depth profile with resolution getting higher towards the surface. [4][10]

TABLE II
Table wetness

Term	Wetness index	Description
dry	1	Usually Ts is below 0°C, but dry snow can occur at any temperature up to 0°C. Disaggregated snow grains have little tendency to adhere to each other when pressed to- gether, as in making a snowball.
moist	2	Ts = 0°C. The water is not visible even at 10x magnification. When lightly crushed, the snow has a distinct tendency to stick together
wet	3	Ts = 0°C. The water can be recognised at 10x magnification by its meniscus between adjacent snow grains, but water cannot be pressed out by moderately squeezing the snow in the hands (pendular regime).
very wet	4	Ts = 0°C. The water can be pressed out by moderately squeezing the snow in the hands, but an appreciable amount of air is confined within the pores (funicular regime)
soaked	5	Ts = 0°C. The snow is soaked with water and contains a volume fraction of air from 20 to 40% (funicular regime).

based on [10], page 8

2) Swiss Ramsonde: As already mentioned in III-A1, the Swiss Ramsonde is a tool for measuring snow hardness. After being predominantly used in soil mechanics due to its robustness and simplicity the Ramsonde got adapted and used in measuring snowpack hardness in the 1930s. The Swiss Ramsonde is a metal pole consisting of several segments with each one measuring one metre in length and weighing one kilogram. The first element has a cone-shaped tip to penetrate the snow cover more easily. Depending on the penetration depth needed, segments can be added upon the first one. The probe is driven into the snow vertically with the weight of a one kilogram hammer as seen in Figure 1. This is done repeatedly until the desired penetration depth is reached. Drop height and number of iterations need to be documented. These observations combined with the penetration depth and the attributes of the probe allow calculating the snow hardness for each individual iteration. Resolution of the Swiss Ramsonde is dependent on the snow hardness due to it being force driven. The maximum resolution achievable is 100 mm in hard snow conditions. [11]

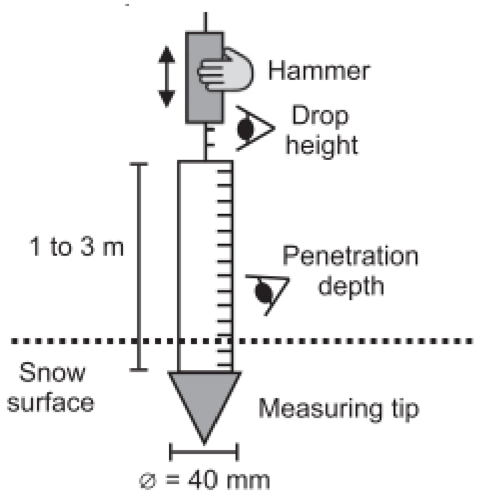

Fig. 1. Ramsonde application schematic based on [11]

3) Snow Micro Pen: The Snow Micro Pen (SMP) is designed in a similar fashion to the first element of the Swiss Ramsonde. It is a pole with a cone-shaped tip that gets driven into the snow cover. In contrast to the Swiss Ramsonde this is performed by a motor mounted on ski poles as shown in Figure 2 . A digital component controls the device and also performs documentation. The assembly is able to drive the probe into the snowpack up to a depth of 0,17 m with a constant velocity of $20\,\mathrm{mm\,s^{-1}}$. The SMP performs 250 force measurements per millimeter with a resolution of 0,01 N and is operational up to 40 N of resistance. In contrast to the Swiss Ramsonde it loses accuracy within hard snow conditions. This is exclusively due to the assembly and not a technical limitation. [11]

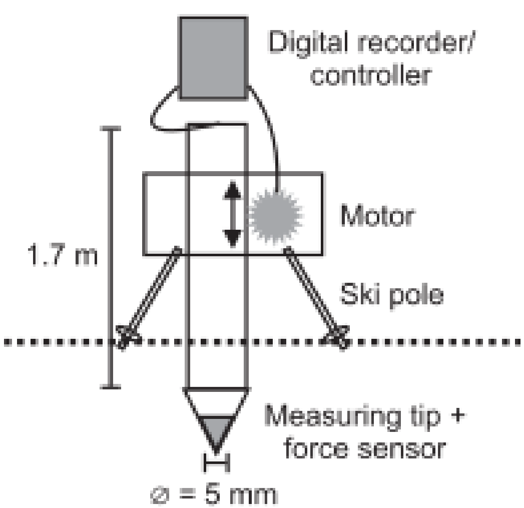

Fig. 2. Snow Micro Pen application based on [11]

4) MountainHub SP2: The SP2 is the latest version of the penetrometer developed by Mountain Hub. It is a handheld device consisting of a metal pole with conic tip and a digital interface controlling the device. The SP2 is driven into the snowpack by hand and can handle depths up to 0,15 m. Functionality is based on infrared sensors, an accelerometer and a force sensor placed in the tip. The infrared sensors estimate the current depth of the device with a maximum resolution of 0,1 m. The purpose of the accelerometer is initializing and ending the measurement by recognizing the vertical movement into the snowpack. The built in force sensor performs one force measurement per millimeter and provides a resolution of 0,7 N while being operational up to 23 N of resistance. [11]

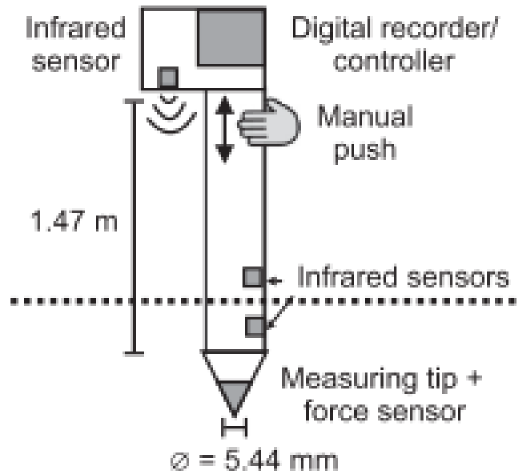

Fig. 3. SP2 application based on [11]

5) Small block test: The small block test is a stability test performed by lateral tapping of a snow block. The excavated snow block should have cross-section dimensions of 0,4 x 0,4 m and a vertical length of one meter. With lateral tapping performed by a shovel the snow block is led to failure. The applied force leading to failure needs to be documented. By visual inspection of the failing layer it is determined if a so called weak layer is present. An important factor in evaluating the failing layer is the kind of fracture occuring. It is differentiated between sudden, rough and stepped fracture planes. Further observations include grain shape, grain size, weak layer thickness, depth of weak layer and snowpack hardness. In comparison to stability tests applying vertical forces, the small block test needs notably less energy to cause a fracture. Additionaly, it is able to detect weak layers significantly more often than other stability tests and has less dispersion regarding stability values. It is recommended to perform this test for at least two locations on different slopes nearby to be able to extrapolate findings onto other slopes in proximity. [5][12]

6) Rutschblock test: For this stability test an isolated block of snow is loaded vertically up until failure. The cross-section dimensions of the isolated block are 2,0 x 1,5 m with around one meter of depth. The stability of the snowpack is determined by the kind of load necessary to cause failure as shown in Table III. Drawbacks of this method are the time needed for performing the test (around 15 minutes), missing evaluation of weak layers below one meter of depth and the importance of choosing a test location representative of the slope. [13]

TABLE III
RUTSCHBLOCK STABILITY

Stability index	Load neccessary to initiate failure
1	Failure under own load of block
2	A person on skis steps on block carefully
3	The person initiates load by rapid knee bend
4	The person on skis jumps
5	The person on skis jumps twice
6	A person without skis jumps onto the block
7	No failure

[13], page 176

7) Compression test: The compression test aims to identify weak layers by tapping on top of a snow block vertically. It is used to detect weak layers in proximity to the snow surface in soft snow conditions. This test requires expert knowledge of the person interpreting the observations. The results regarding snow stability are highly dependent on variables inside the snowpack like stratigraphy, snow hardness and depth of identified weak layers. A block of snow with cross-section dimensions of 0,3 x 0,3 m and a depth of 1 m to 1,2 m is isolated. A shovel is positioned flat on top of the isolated block and loaded in different steps. Each one of these steps follows a predefined tapping force and number of taps. The observations are documented and interpreted following Table IV. In any case of failure the depth of the failing layer is recorded and documented. To determine snow stability a shear quality should be included in interpretations of the results.

TABLE IV
COMPRESSION TEST STABILITY

Failure index	Load neccessary to initiate failure
Very easy	Failure during cutting
Easy	Failure before 10 light taps using fingertips only
Moderate	Failure before 10 moderate taps from elbow using fingertips
Hard	Failure before 10 firm taps from whole arm using palm or fist
No failure	No failure achieved

based on [13], page 177

8) Extended column test: The extended column test is performed following the schematic of the compression test. Using a snowblock with cross-section dimensions of 0,2 x0,9 m, the focus lies on characterizing observed fractures. [5]

B. Snow profiling using an Unmanned Aerial Vehicle

In this section a new approach to getting information about snow composition that can be used in avalanche forecasting is presented. All of the methods to analyze snowpack mentioned above require either ski patrols, avalanche experts or freeriders to enter the slope of interest. In areas with unknown or high avalanche hazard this poses a significant threat to the health of persons performing these analyses. A UAV in contrary allows for remote missions without entering dangerous areas of the mountain. The UAV can be controlled from a stationary outpost like a mountain station or even set up for autonomous missions. The main application possible with such an UAV is the delivery of a Snow Profiling Device similar to the Snow Micro Pen and SP2 to a slope of interest. Dropping this device into the snowpack from a specific height enables a calculation method similar to the Swiss Ramsonde method. The known parameters drop height and device weight allow calculation of impact energy. Sensors inside the SPD document the propagation into the snowpack. An accelerometer provides information about deceleration while a force sensor measures resistance of different snow layers. In combination with penetration depth a snow profile can be recorded and documented.

The payload interface developed for this application contains the remote controlled Muscle Winch [14] and an actuating servo mounted on a carrier platform. The actuating servo is capable of dropping the SPD by activating a freewheel function built into the winch. After measurements are completed, the winch can reel in the SPD. Both of those operations can be performed independently from each other by the simple switch of a button on a RC-transmitter.

To reliably transport a device similar to the digital penetrometers presented in Section III-A, the drone needs sufficient lifting power. Using the multicopter sizing methodology presented by Biczyski et al. [8], a propulsion system capable of handling a 5 kg payload was calculated. As shown in Figure 4, this octocopter is able to achieve a flight time of around nine minutes with a payload of 5 kg attached. This already takes the reduced air pressure in alpine areas into consideration. In case of a device as light as the SP2 the same UAV is able to stay in the air for 16 minutes as shown in Figure 5. Since the payload interface is able to perform more than one drop/pickup cycle in one mission, such a flight time allows several measurements in one flight. Since the only limiting factor in flight time is the battery pack, extensive analysis of surrounding slopes can be performed when using ”pitstops” to change the battery pack. This enables flexible mission planning for areas of interest in the mountain.

The flight control of the UAV consists of a Cube Orange flight-controller using the Ardupilot software, a FRSky R9 receiver and a FRSky transmitter. This allows reliable operation from up to 10 km distance and the option to setup autonomous missions [15].

IV. DISCUSSION

The ability of the UAV to target several spots in the mountain makes it a more versatile option compared to manned missions using a Swiss Ramsonde, SnowMicroPen or SP2. This facilitates performing several measurements leading to a higher certainty regarding the results. In addition, results from different slopes in near proximity can then be extrapolated to cover wide areas of mountain terrain as stated in [12]. Furthermore, the health and well being of avalanche experts, ski patrollers and freeriders can be ensured when using UAV-assisted field observations instead of manned missions. Another advantage of UAV-aided snowprofiling is reproducibility. Modern telemetry and autopilots can ensure a specific dropping height, resulting in almost identical impact energy of the SPD for every measuring cycle.

Compared to the stability tests presented in Section III-A the Snow Profiling Device in combination with a standardized drop height can provide more objective measurements [11]. The method by Fierz et al. [10] for example, requires mountaineers to perform multiple steps to get an assessment of the snow conditions. These include creating a snowpit and performing observations on the exposed snow layers. Combined with a hand hardness test described by Viallon-Galinier, Hagenmuller and Lafaysse [4], the condition of the snowpack can be evaluated subjectively. With and SPD dropped by a UAV on the other hand, these observations and estimations would be obsolete due to the objective measurements performed in one step. The Swiss Ramsonde also is capable of performing snow hardness measurements in only one step [11]. Its resolution and accuracy is relatively low however, since it is driven into the snow with a hammer by hand [11]. When dropping an SPD with a drone, the height data provided by telemetry can be observed and documented on the RC transmitter [15]. This allows precise calculations regarding the penetration energy, mitigating any inaccurracies due to human intervention.

Drawbacks include high cost of UAV systems and development of a SPD delivering reliable results in UAV-missions. To ensure proper operation of the UAV, users would need to undergo training, possibly resulting in additional costs and rejection among experts. Also performing any kind of stability test presented in III-A is not possible using a UAV in combination with a SPD. Vital information about grain shape, grain size, fracture geometry and crack propagation can not be recorded. This results in the additional need for manned mission performing stability tests in these areas or the waiving of this data.

V. Conclusion

While currently used methods and tools used for snowpack analysis are essential for reliable avalanche prediction some of them use outdated technology. Avalanche experts, ski patrols and freeriders need to enter unknown and sometimes dangerous areas regarding avalanche hazard to perform measurements. With the help of an UAV in contrast, people can provide quick and safe information about areas of interest without having to take any health risks. While an UAV can not perform all of the measurements necessary for snowprofiling it can reduce the amount and duration of manned missions into slopes of interest.

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Appendix A
UAV dimensioning

Fig. 4. Octocopter optimized for a payload of 5 kg. Based on [16]

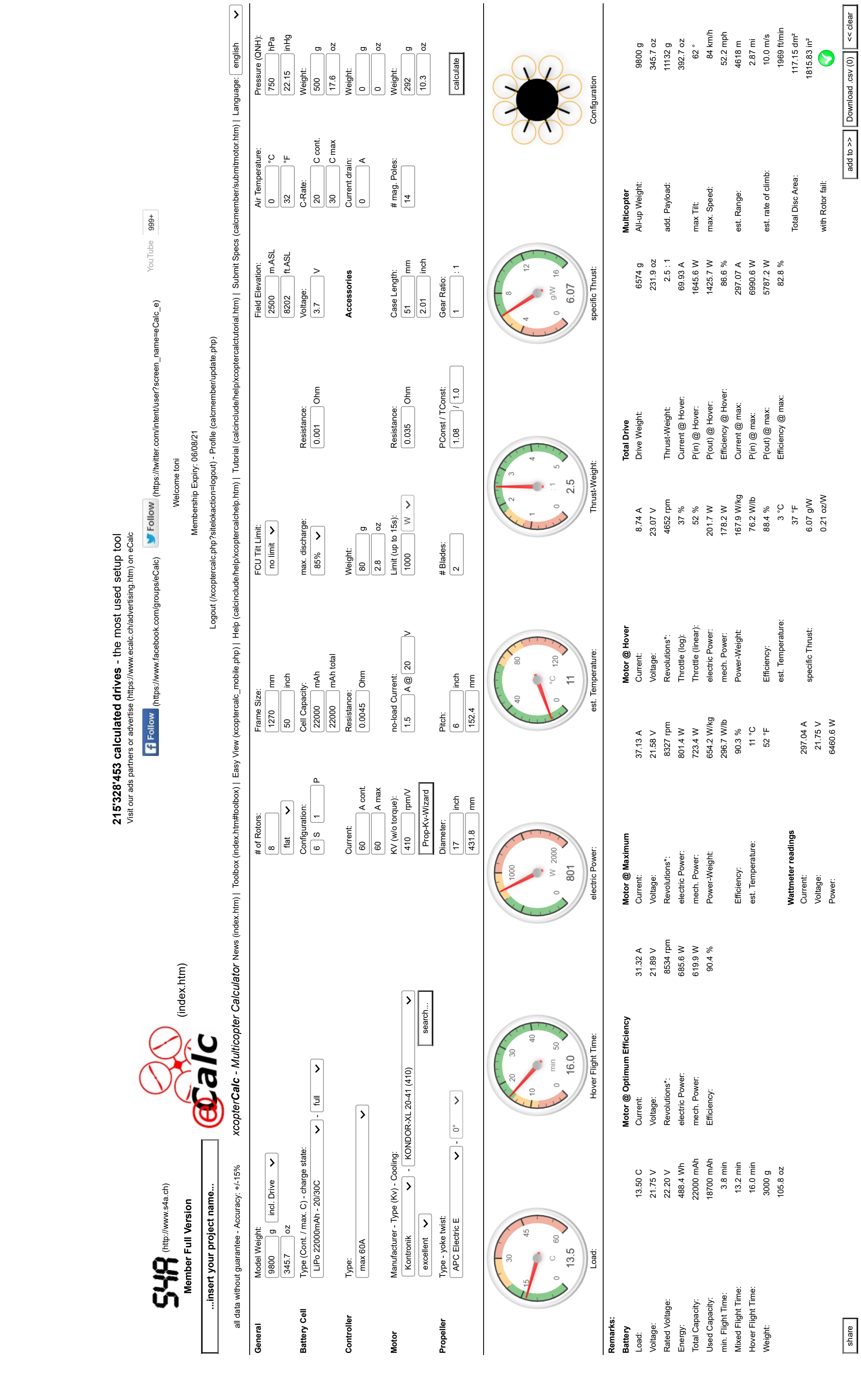

Fig. 5. Flight time with a payload of 0,6 kg attached. Based on [16]