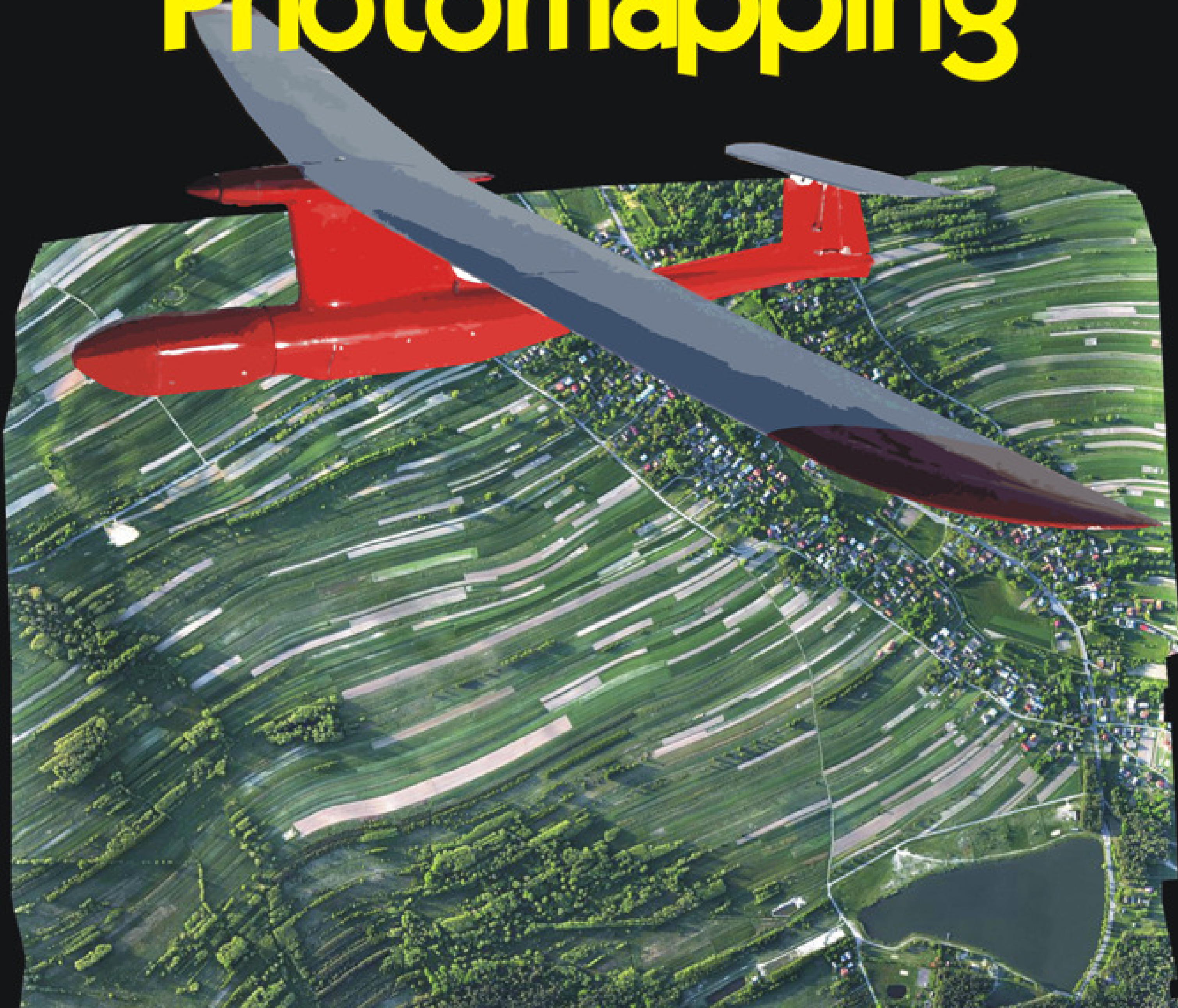
Secrets of Photomapping



By

Krzysztof Bosak

PTERYX

'Make things as simple as possible, but not simpler'

A. Einstein

Title page: 4.5km^2 ortophotomap at 10cm/pix created with Pix4D

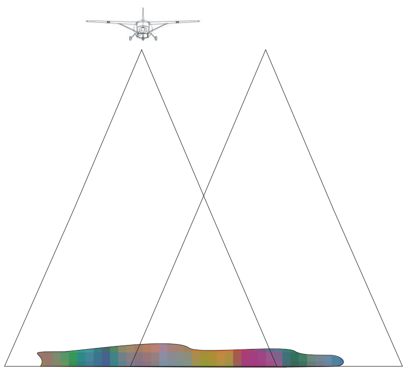
GPS and IMU precision

We are frequently asked about usefulness of advanced DGPS solutions to be used for referencing having ‘more precise solution’ or more precise IMU.

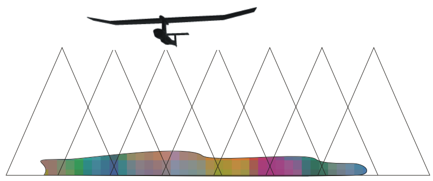
Bad news is that airborne GPS or IMU in small flying objects are never going to be as precise as stationary GPS. This is because the measurements are less correlated in time and the object is subject to constant vertical accelerations due to atmospheric turbulence.

Good news is it is not needed as the precision comes from imaginery, up to three thousand photos, each tagged with its own position and orientation. The measurements are so precisely linked together that their large number provides accuracy.

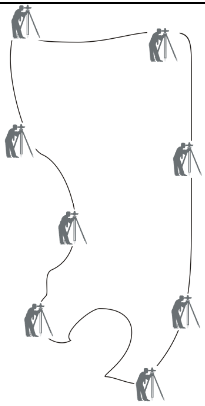
Operational practice says that using DGPS would only add unnecessary complexity to the system, requiring robust long range uplink that cannot be provided given power restriction for regular (non-registered amateurs) modem users in most countries, for typical operational distances. The GPS in Pteryx UAV is using existing WAAS and EGNOS ionospheric transmittance correction data which are transmitted by the satellites.



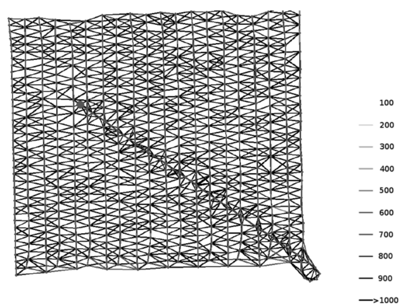
500-2500m flight altitude
Wide coverage, but less features per object to correct orientation.



Typically 100-300m flight altitude
Large numbers of GPS measurements matching on terrain feature provide enhanced precision.

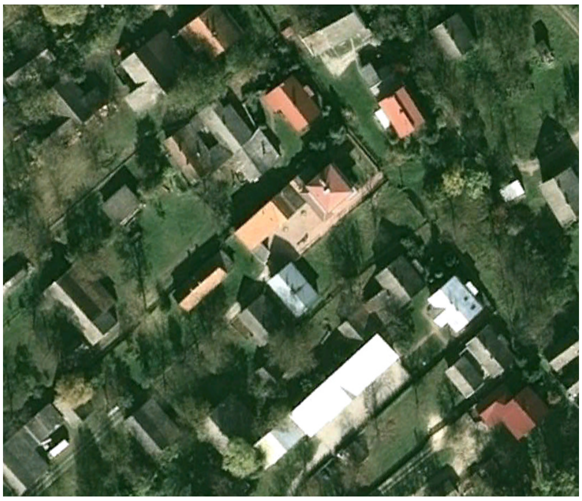
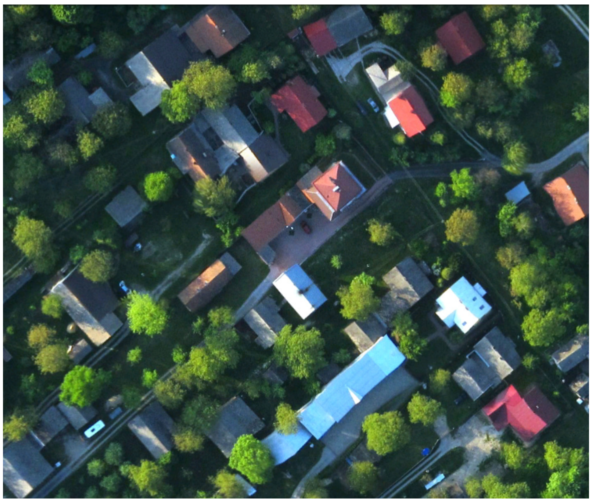
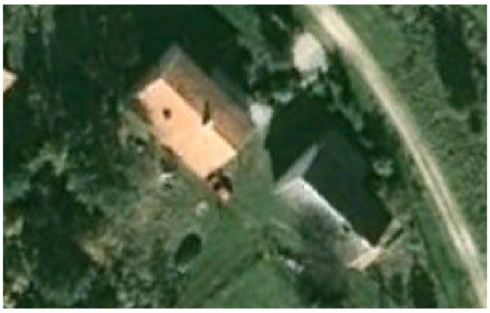
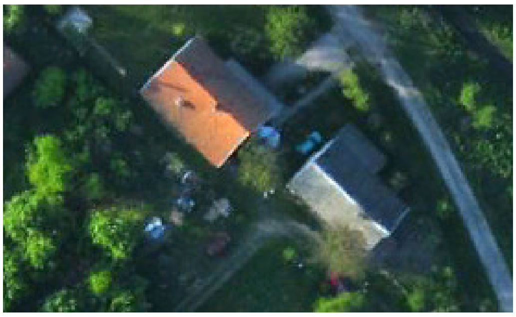


Traditional GPS surveying:
Each measurement point is static, but uncorrelated to neighboring measurements therefore highest precision is desirable.



More than a thousand features link each neighboring image, creating a map with global sub-pixel geometric accuracy.
Optional 3-4 control points can shift the map, reducing error from a few meters to stationary GPS precision (around 10cm).

Full scale aviation vs small UAV imaginery

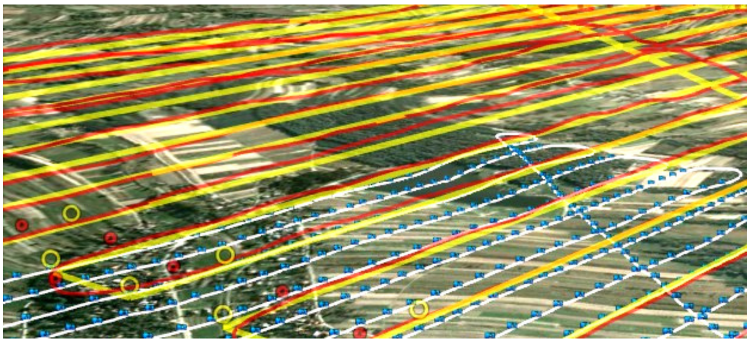
 2011, recent equipment aboard airplane, flight altitude around 1500m, visible green cast on the whole map. 10cm/pixel resolution. Shadows have severe impact on data.	 Pteryx, flight altitude 300m AGL Much less air between the sensor and target, same resolution, significantly better color definition. More information per pixel!
 All buildings are often uniformly tilted to the side, however at small angle as long as flight altitude is high.	 Distortion is removed thanks to photos covering the target from all angles. True ortophoto is a standard!

Full scale aviation vs small UAV imaginery - continued

	Full scale airplane	**Pteryx UAV**
Flight duration	Up to 2 hours	Up to 2 hours
Personnel involvement	2 pilots typically with bi-engine qualifications CPL(A), IFR, MEP(L), 1 onboard system operator	1 pilot, sometimes with 1 helper/observer
Area coverage per flight	Hundreds of square kilometers	Around 9km^2 (900ha) for rectangular map per flight, Up to 72km^2 (7200ha) for straight-line flight (depending on resolution).
Resolution	500-2500m AGL Lower altitude limited by noise, regulations and risk involved (urban areas, time to ground).	4cm/pix at 100m AGL 11cm/pix at 300m AGL Upper altitude limit often imposed by air traffic laws.
Capital investment	Custom-equipped, typically 4-place bi-motor general aviation aircraft.	100..200 times less capital investment, the UAV reuses existing computers, possible subscription to online cloud processing service, the sensor is high quality consumer market camera.
Environmental impact	Noise limits. Uses aviation fuel.	Completely inaudible above 200m, except at night without any wind. Rechargeable electric power.
Mission readiness	Must return to airfield.	Can be stored close to mission area waiting for clear weather.

UAV can deliver better quality maps, where using full scale aviation would be a nuisance. UAV operates locally, but covers areas inaccessible to occasional aerial solutions including paraplanes, ad-hoc RC airplane installations or kites.

Typical UAV flight path



Resolution, megapixels and flight altitude

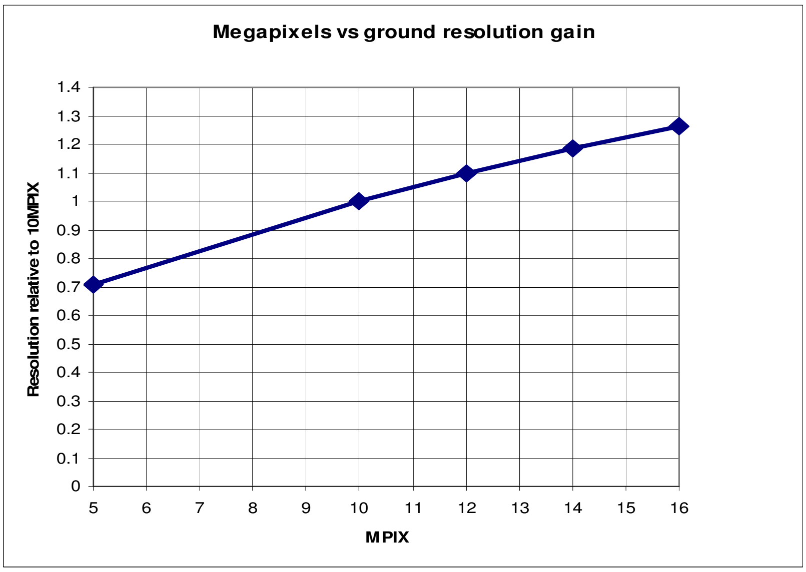
Pteryx Pro has built-in 10MPIX camera, using standard lens.
This translates into 66 deg horizontal viewing angle.
The user selects flight altitude in order to

- avoid obstacles with at least 80m clearance
- assure comfortable angular distance to obstacles (visual contact)
- meet law requirements (max altitude either 400ft, 300m or other, depending on country and ATC rules)

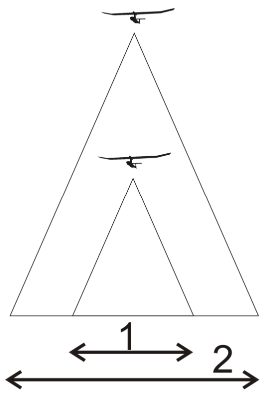
In general one chooses to fly as high as possible in order to fly shorter missions.
The altitude indicated is approximate, since terrain altitude variations are present. On the other hand geometric precision is not reduced because each point of geometry is shared among many photos providing ample reserve of accuracy. Of course ground-projected texture resolution will degrade in mountain regions.

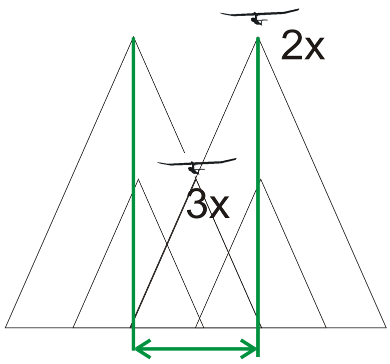
Altitude [m] (ft)	**Resolution [cm/pix] (in/pix)**	**Ground photo width [m] (ft)**
100 (330)	**3.5 (1.4)**	**129 (423)**
122 (400)	**4.3 (1.7)**	**157 (515)**
140 (460)	**5 (2.0)**	**180 (590)**
200 (660)	**7.1 (2.8)**	**257 (843)**
280 (920)	**10 (3.9)**	**360 (1181)**
420 (1380)	**15 (5.9)**	**540 (1771)**
560 (1840)	**20 (7.9)**	**720 (2362)**

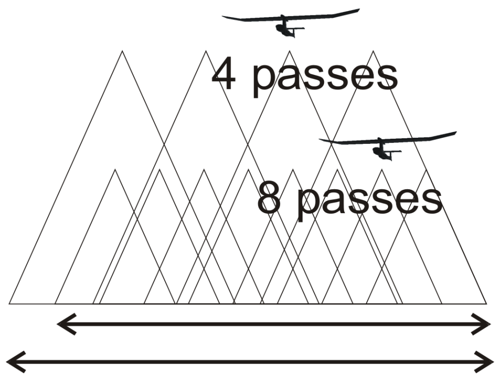
Linear ground resolution depends on megapixel count using square root law,
For example switching from 10 to 14mpix camera yields only $\sqrt{\frac{14}{10}} = 18\%$ more linear resolution. Alternatively one could have 18% higher altitude, 18% more sparse mapping pattern but in practice only 10-15% more area coverage (because one must include climb time). Therefore our camera choice is motivated mainly by lens properties. All this assuming that 14MPIX camera will have not worse noise properties than 10MPIX camera.



Surface, map shape and flight altitude

<table>
<tr>
<td>

I you are mapping a linear object, doubling the altitude you are **doubling surface** coverage</td>
<td>

If decided to make 2 passes hoping to improve geometry matching, because of overlap requirement, **flying high** you are **reducing flight time only by about 1/3,** because outside regions have valid bitmap but poor geometry.</td>
<td>

With regular map shape and multiple passes, flying 2 times higher needs 2 less passes and flight time and provides extra surface at map edges. However, the area should be flat as there will be no multi-angle information allowing to orthonormalize high objects along the edges.</td>
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</table>

It is easy to witness large mapping areas with UAV flying straight. In fact, flying straight with Pteryx for 2 hours at 50km/h at altitude of 560m, yields 20cm resolution and ground photo width of 720m.
Using the formula:

$$S_{STRAIGHT\_FLIGHT}[km^2] = T \cdot V \cdot W$$
$$T[h] - flight\ time$$
$$V[km/h] - speed\ over\ ground$$
$$W[km] - ground\ photo\ width$$

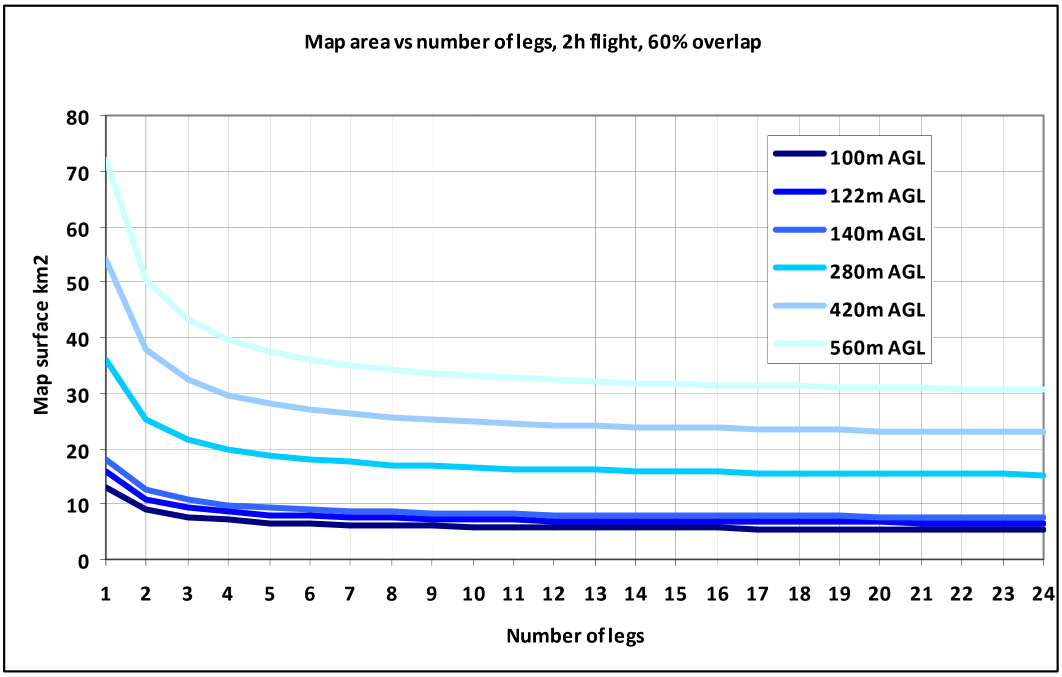
One easily can deduce **72km^2 map surface in a single direction straight flight.**
However, assuming returning flight and only 60% overlap, one gets (100%+40%)*720m=1008m strip width and only one hour of flying in one direction.
This yields only **50.4km^2 map surface with returning flight**.

<table>
<tr>
<td>
A single-leg mission. Typical along-overlap is high, around 75..90%.</td>
<td>
Two-leg mission. Typical 60% side-overlap shown. Along-overlap 75..90%.</td>
<td>
Three-leg mission. Typical 60% side-overlap shown.</td>
</tr>
</table>

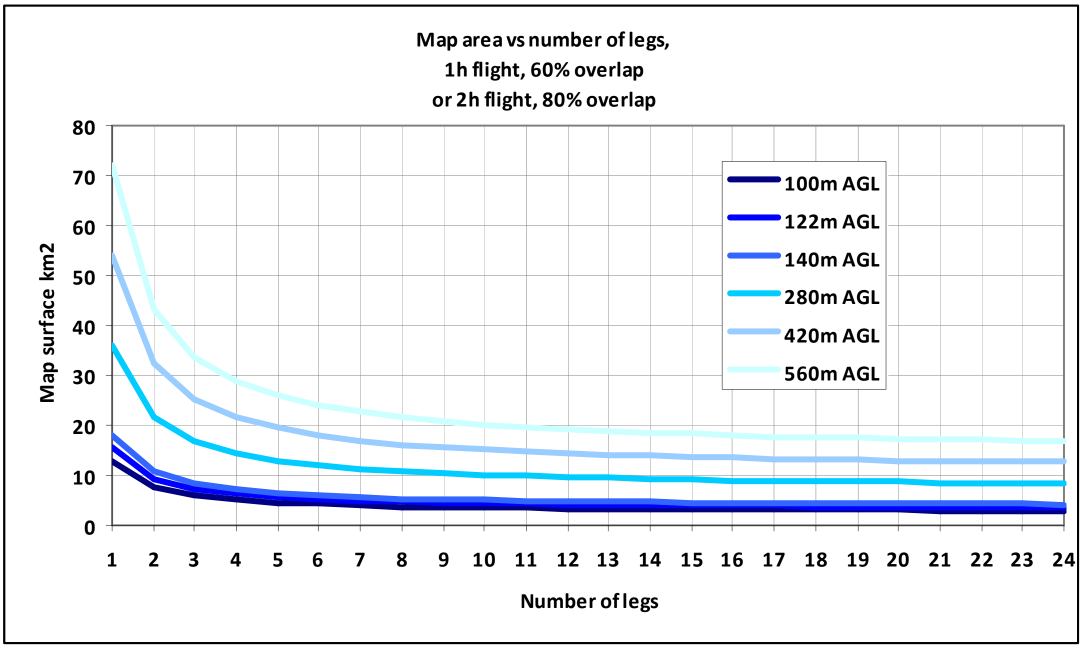
In the following plots, square map exhibits similar properties as 9...10 leg maps.

Note: $1km^2$=100ha=247 acre=0.386sq mi=10764sq ft

Assuming typical **60%** overlap, 50km/h airspeed, no wind and 2h flight, we get the following surface figures depending on number of legs:

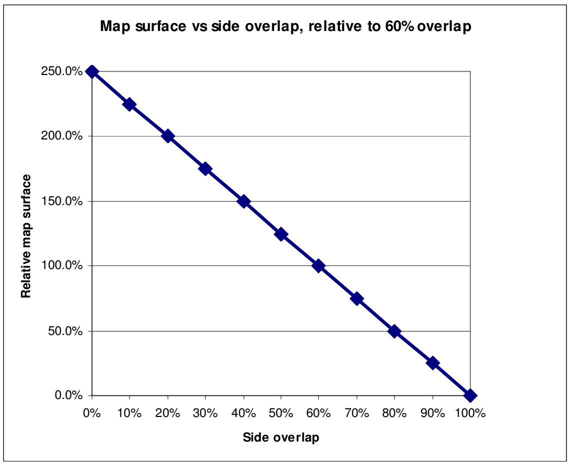


Assuming typical **60%** overlap, 50km/h airspeed, no wind and **1h** flight
or
80% overlap for demanding applications, 50km/h airspeed, no wind and **2h** flight, **divide the surface roughly by two** (note that 1-leg flight surface is unaffected):

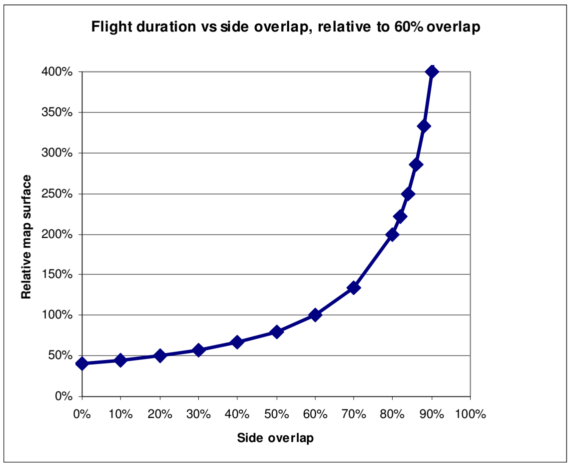


Side photo overlap

In Pteryx the camera is arranged with base parallel to wings.



For regular map shape when flight legs must overlap, the surface mapped in unit of time diminished with growing overlap.



Inevitably, flight duration rises dramatically with overlap. It is crucial to find and always satisfy minimal overlap required by processing software.

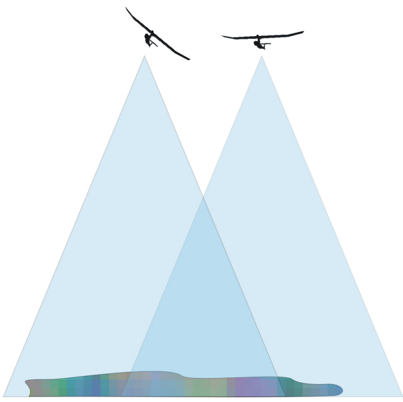
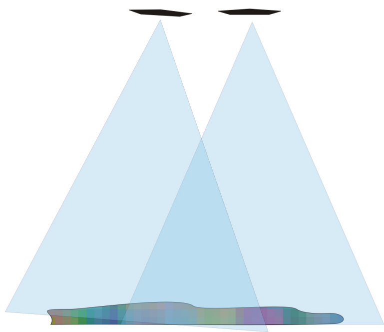
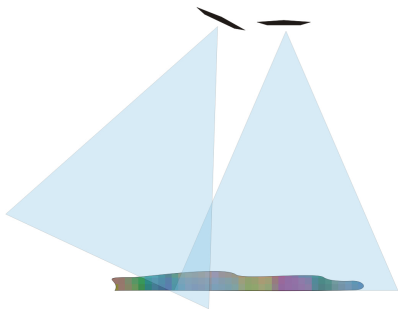
While using smallest possible overlap is tempting, it may lead to increased data processing failure rate over specific terrain, with low contrast. It is necessary to keep slightly higher overlap in urban areas; this is subject to experimentation with specific choice of processing software and requested precision during orthonormalization.

Our experience indicates that:

- 40% side overlap is sufficient only in exceptional cases with high contrast terrain, but it must be flat since protruding objects like building will highly distort area around them, i.e. roads. Therefore it would be sufficient for agriculture, if not the fact that the subject is monotonous and low overlap may generate false matches. Because of this we do not recommend mapping with such low overlap. It also leaves no room for a blurred photos to be removed before stitching.
- 60% side overlap is acceptable in rural areas, agriculture and in forestry. It is also sufficient for 3D terrain mapping if the main goal is volume/profile measurement.
- 70-80% side overlap is preferred in built-up areas with towers, 5-story buildings or in sloped mountains where specific features must retain resolution and precision.

Importance of stabilized head

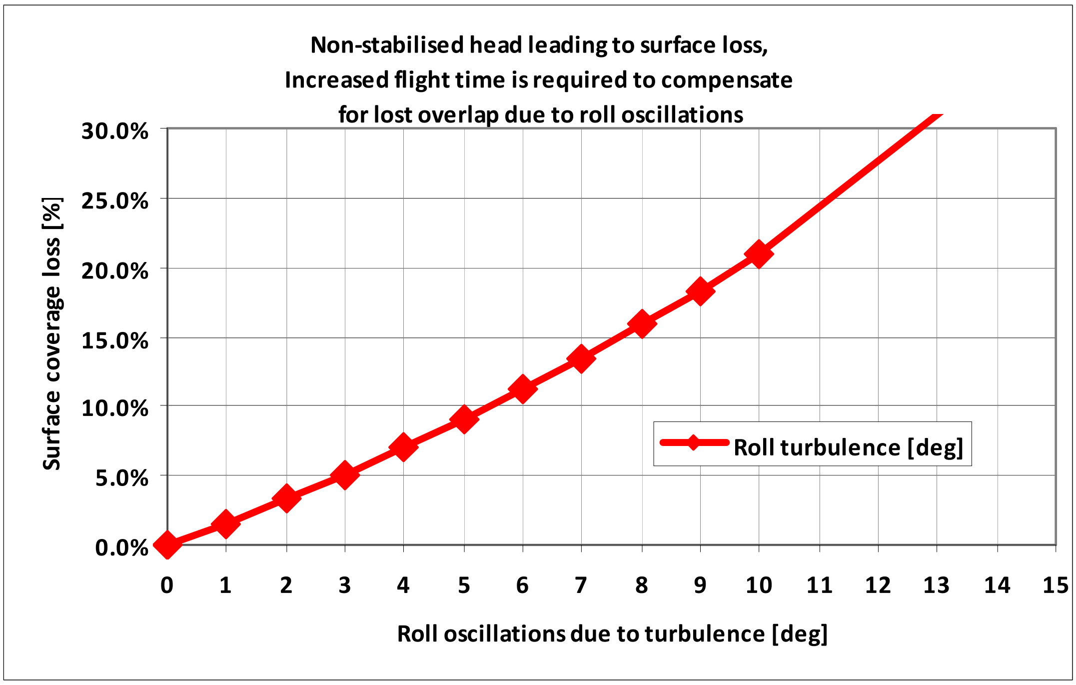
Since increasing overlap is so costly in mission time and so important in urban areas,
Pteryx uses roll-stabilized head and has aerodynamic design successfully attenuating oscillations in pitch and yaw axes.
The use or roll-stabilized head increases useful surface during turns and increases processing success rate thanks to overall more predictable photo properties.
Unfortunately all smart-looking small flying objects are also small relative to typical size of turbulent cell in the air, therefore their roll and pitch depends more on wind conditions.
Stiff automated control of small aerial platforms with active control surfaces leads to significant short-term movements, causing occasional blur in the photos. Stabilized head and special aerodynamics layout with exceptional damping properties comes to the rescue.

 With stabilized head, the overlap stays guaranteed, even in turns.	 Without stabilized head, typical deviations of a few degrees already require extra few percents of overlap pre-planned. This is costly in terms of flight time and worsens significantly during windy weather.	 Without stabilized head, photos taken during turns are completely useless for reconstruction, typically overlapping by few degrees and only in corners. No airplane can make a full turn that is flat (with reasonable radius). Those photos cannot contribute to enhancing map geometry inside the area of interest.

Both small UAV like flying wings and even large UAV with several meters wingspan tend to respond for navigation with changing 0-5 deg roll both directions even when ordered to 'fly straight' over ground. The reason is, while ground path is straight, the wind blows in any direction, usually as much as 45 deg different at altitude than at ground level, with little direction change but much more wind speed variation. This means the UAV has to bank left and right all the time in order to stay on its path. On the other hand we have seen earlier that increasing number of legs costs flying time, therefore it is possible (and implemented in Pteryx UAV) but highly impractical to rotate elongated flying pattern against the wind.

Using stabilized head, we are freeing you from one more mission planning factor: you fly in the direction you like.
It is interesting to think how all types of small flying things perform in this area. RC flying models notoriously bank at 45deg and fly uneven path +/- 10deg roll both sides until the pilot is in good mood. Kites are worst, tumbling in all direction requiring many photos to be taken and the good one chosen. It is impractical to select one thousand photos among several thousand per few square kilometers.

Assuming 66.5 deg wide view angle determining the leg spacing, at any altitude or airspeed:



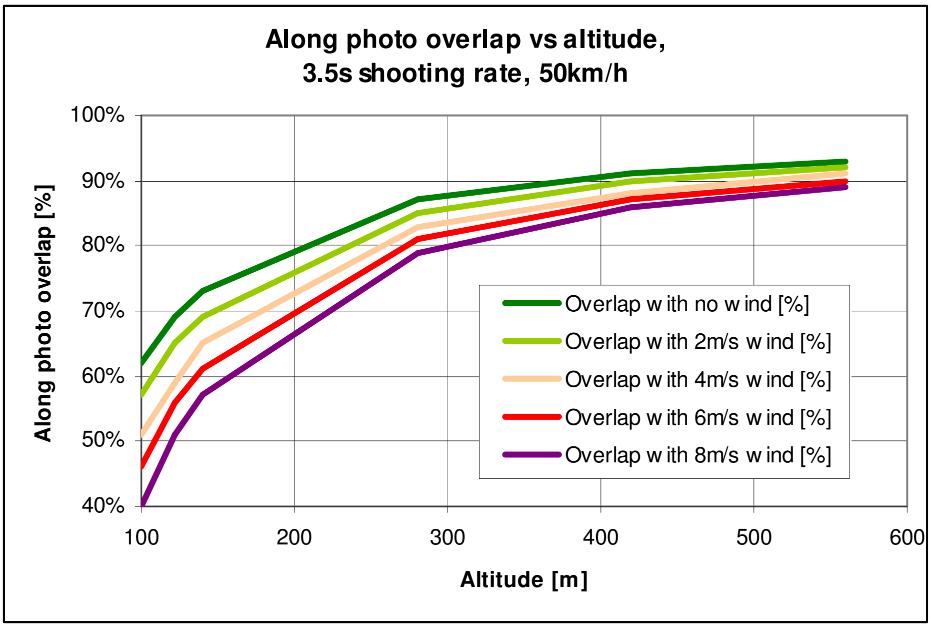
The effect is nominally not large until you assume a priori the correct spacing and flight time before takeoff. There are no strategies available to correct this in flight, if you over-optimize, failed overlap reveals itself post-flight. That is, if you don't have stabilized head.

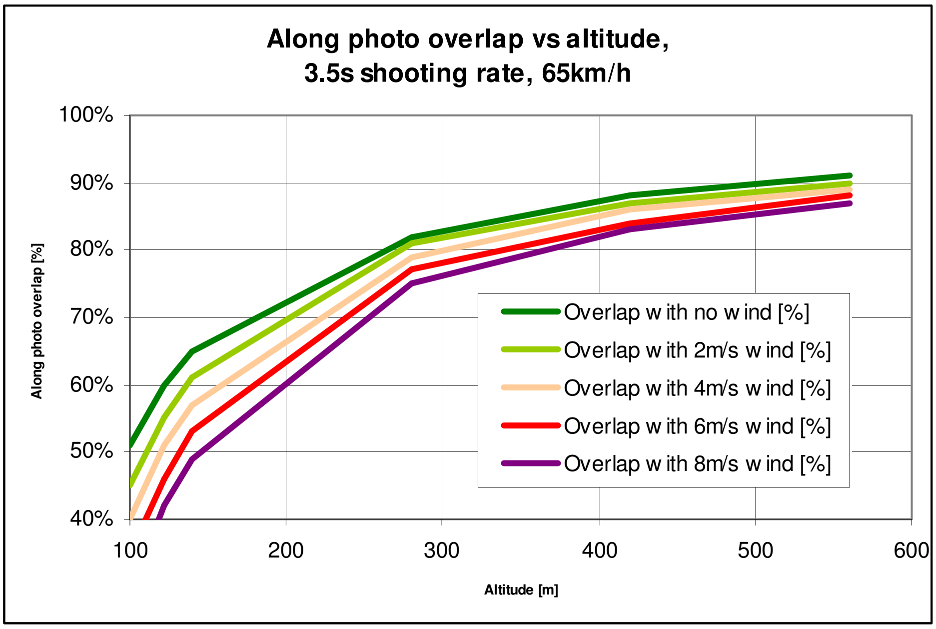
If you fail to plan ahead, while weather worsens, the processing result might be as follows:

Non-stabilized head, locally reduced overlap led to mismatched road geometry.
Pteryx UAV is completely free from those troubles.

Along photo overlap

Along photo overlap is a result of high rate of shooting of the camera. The worst case occurs when the plane flies with the wind, when the overlap diminishes below acceptable margin, we assume here 60% but it depends on processing software. At high altitude, the overlap is so high that continuous shooting yields beneficial backup photos, allowing deleting any single blurred photo. One can conclude, that in windy weather, when ground-induced turbulence is highest at lower altitude and more blur is expected there is no room for backup photos. Flying at higher airspeed only worsens the situation; flying at lower airspeed drastically reduces area covered due to heading. The camera continuous shooting rate is the limit. **It should be noted that camera's truly continuous shooting rates are never published – each single camera make has to be tested individually as we are talking about 2 hours of continuous shooting.**





Number of photos taken and data quantity

It is recommended to use the least compression possible. However, many processing systems are more convenient using EXIF data from JPG format. Upload time is better when using some compression. For Canon S90 at typical flight altitude the compression artifacts are significantly smaller than contrast loss for aviation medium-altitude data.
Assumed shooting rate 3.5s as it requires focusing without any missed data.
Using remote services is limited mainly by upload speed of ADSL connections.

Source data:

Photo size Canon S90 10MPIX [MB]:		3	14	3	14	3	14	3	14
Flight time [min]	Photo count	JPG photo estd. max size [GB]	Raw photo estd. max size [GB]						
30	515	1.6	7.1	1.6	7.1	1.6	7.1	1.6	7.1
40	686	2.1	9.4	2.1	9.4	2.1	9.4	2.1	9.4
50	858	2.6	11.8	2.6	11.8	2.6	11.8	2.6	11.8
60	1029	3.1	14.1	3.1	14.1	3.1	14.1	3.1	14.1
70	1200	3.6	16.5	3.6	16.5	3.6	16.5	3.6	16.5
80	1372	4.1	18.8	4.1	18.8	4.1	18.8	4.1	18.8
90	1543	4.6	21.1	4.6	21.1	4.6	21.1	4.6	21.1
100	1715	5.1	23.5	5.1	23.5	5.1	23.5	5.1	23.5
110	1886	5.6	25.8	5.6	25.8	5.6	25.8	5.6	25.8
120	2058	6.1	28.2	6.1	28.2	6.1	28.2	6.1	28.2

Note: in real flight assume 15-25min post-takeoff, pre-landing and turns.

Typical upload times:

	Bandwidth:	512kbps 512	512kbps 512	1Mbps 1024	1Mbps 1024	2Mbps 2048	2Mbps 2048	10Mbps 10240	10Mbps 10240
Flight time [min]	Photo count	JPG time[h]	Raw time[h]	JPG time[h]	Raw time[h]	JPG time[h]	Raw time[h]	JPG time[h]	Raw time[h]
30	515	7.3	32.3	3.6	16.2	1.8	8.1	0.4	1.6
40	686	9.6	42.8	4.8	21.4	2.4	10.7	0.5	2.1
50	858	11.8	53.7	5.9	26.9	3.0	13.4	0.6	2.7
60	1029	14.1	64.2	7.1	32.1	3.5	16.0	0.7	3.2
70	1200	16.4	75.1	8.2	37.5	4.1	18.8	0.8	3.8
80	1372	18.7	85.6	9.3	42.8	4.7	21.4	0.9	4.3
90	1543	20.9	96.0	10.5	48.0	5.2	24.0	1.0	4.8
100	1715	23.2	107.0	11.6	53.5	5.8	26.7	1.2	5.3
110	1886	25.5	117.4	12.7	58.7	6.4	29.4	1.3	5.9
120	2058	27.8	128.3	13.9	64.2	6.9	32.1	1.4	6.4

Note: in real flight assume 15-25min post-takeoff, pre-landing and turns.

Using RAW data is possible only with exceptional speeds, or locally. Local processing requires significant investment both in software and manpower. Agreements about placing processing centers abroad are negotiable with cluster computing service providers.

Result data size

Resulting data size is largely independent on resolution and flight altitude, because as already shown the linear resolution is inversely proportional to altitude. However because of flight time, one can expect fewer gigapixels from high altitude flight.

For 2h Pteryx flight one gets 5-10GPIX depending on pattern shape. Using RGB encoding, 24bpp, one has about 15-30GB to download if the data is uncompressed. In fact a factor of 5 compression of the output data is achieved, leading to input data size being comparable with output data size. The demand for having DEM roughly doubles the data quantity.

Typical download times:

RESULTS Ortophoto only	**Bandwidth -->**	**1Mbps**	**1Mbps**	**10Mbps**	**20Mbps**
	kbps	**1024**	**5120**	**10240**	**20480**
	kBps	**128**	**640**	**1280**	**2560**
Flight time [min]	**Source photo count**	**Time[h]**	**Time[h]**	**Time[h]**	**Time[h]**
30	515	33.1	8.3	2.1	0.1
40	686	43.5	10.9	2.7	0.1
50	858	53.9	13.5	3.4	0.1
60	1029	64.2	16.1	4.0	0.2
70	1200	74.6	18.6	4.7	0.2
80	1372	84.9	21.2	5.3	0.2
90	1543	95.3	23.8	6.0	0.2
100	1715	105.6	26.4	6.6	0.3
110	1886	116.0	29.0	7.2	0.3
120	2058	126.3	31.6	7.9	0.3

RESULTS Ortophoto and DEM	**Bandwidth -->**	**1Mbps**	**1Mbps**	**10Mbps**	**20Mbps**
	kbps	**1024**	**5120**	**10240**	**20480**
	kBps	**128**	**640**	**1280**	**2560**
Flight time [min]	**Source photo count**	**Time[h]**	**Time[h]**	**Time[h]**	**Time[h]**
30	515	66.3	16.6	4.1	0.2
40	686	87.0	21.7	5.4	0.2
50	858	107.7	26.9	6.7	0.3
60	1029	128.4	32.1	8.0	0.3
70	1200	149.1	37.3	9.3	0.4
80	1372	169.8	42.5	10.6	0.4
90	1543	190.6	47.6	11.9	0.5
100	1715	211.3	52.8	13.2	0.5
110	1886	232.0	58.0	14.5	0.6
120	2058	252.7	63.2	15.8	0.6

While the network download/upload time is dominant, this is mostly because of the speed of processing cluster. Local processing of several km^2 might easily take days on the most powerful PC in existence.

The proposed processing service is state of the art design. Hence one might observe that sometimes quoted on-site processing is possible only for the smallest areas that typically do not exceed $0.5km^2$ with additional restrictions on resolution.

Flight speed, wind penetration and endurance

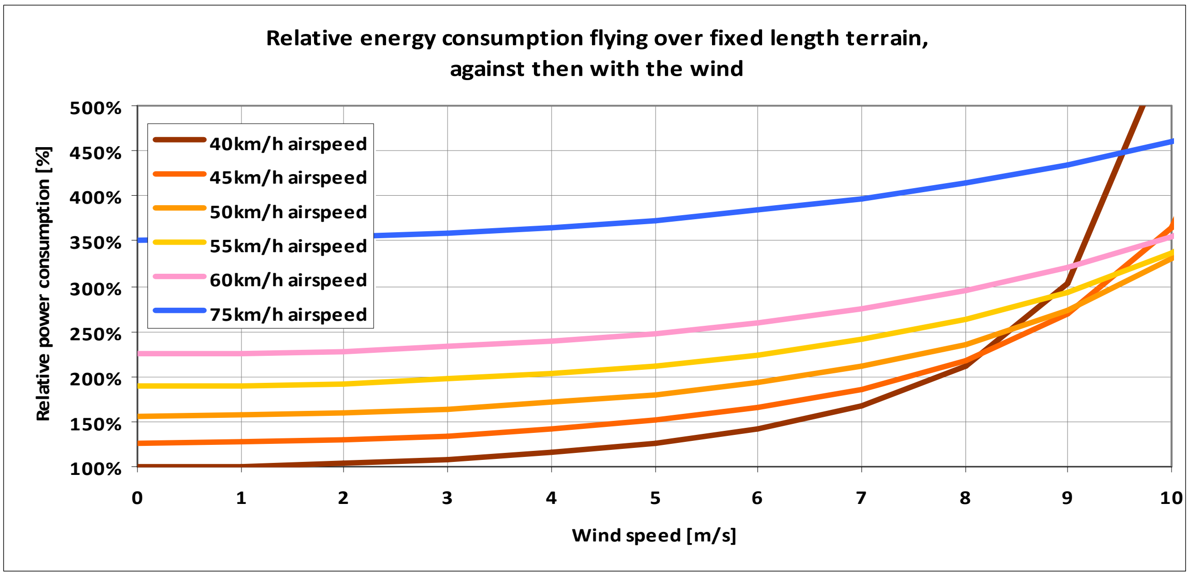
Contrary to intuition, wind speed is never 'helping' enough to catch up the flight time lost flying in headwind. An extreme example occurs when airspeed is equal to wind speed. In such case flying time with the wind is two times shorter, but flying against the wind is not advancing terrain coverage at all, leading to infinite required flight time.

One must remember official limitation of 7m/s wind speed for using Pteryx.
It is important to note that this figure means wind speed at flight altitude,
what as a best guess is 2-3m/s more than on ground level.
This is a practical rule limited by:

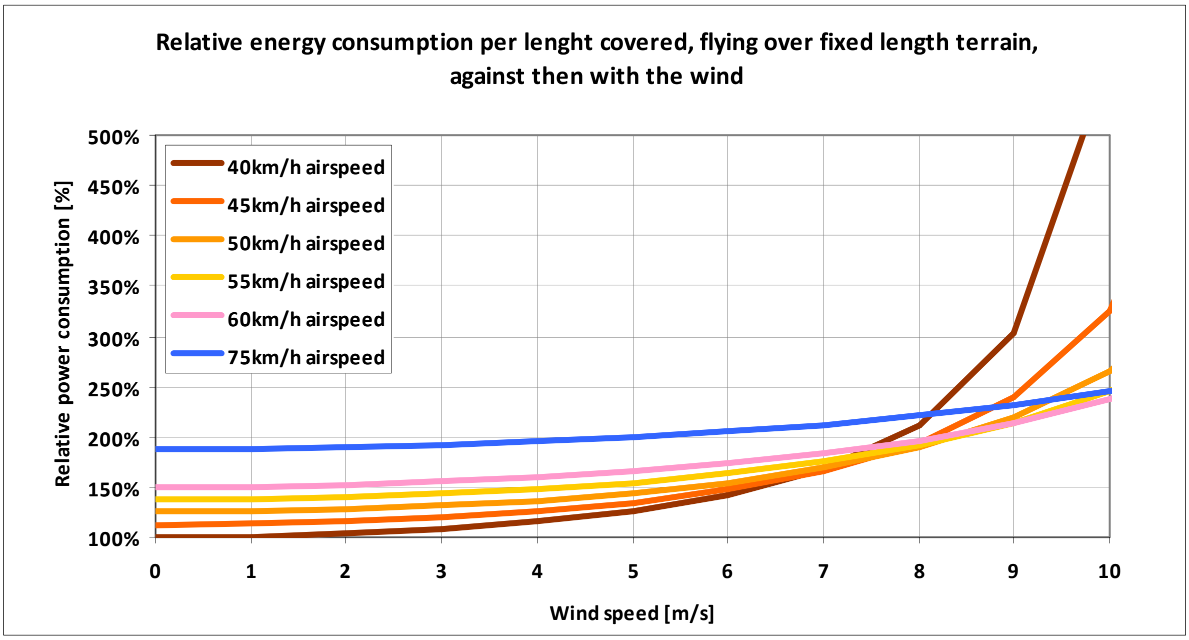
- limited camera shooting rate when flying with the wind at low altitude
- high turbulence and high probability of blurred photos associated with stronger winds, more pronounced angular movement at high altitude (this is greatly reduced by platform layout)
- required flight endurance growing to unreasonable periods of time (this is mitigated by ample endurance reserve)
- less precise parachute planning in case of manually triggered landings
- more risky, less comfortable manual piloting leading to mishaps; forcing using parachute for landing all the time

The combination of above factors affects all small UAVs. Pteryx is offering balanced 'failed mission' probability evenly distributed among before mentioned factors. The wind speed limit is a combination of mission planning and luck plus human factors and as such can be easily exceeded, but it is unreasonable to exceed this limit during regular business operations for which the machine has been designed.

The following plot assumes flying fixed distance with, then against the wind, also taking into account that for airplane of this size+speed energy consumption rises as third power of airspeed. It can be clearly seen that flying at high speed is beneficial practically only in manual mode at full throttle when one must return to base being caught unaware by coming storm (wind speeds above 8m/s), in this scenario Pteryx is able to cruise at around 22m/s for a few minutes.



Things get a little more optimistic when we take into account, that flying faster is consuming more energy, but also the linear distance flown, no matter the wind, is increasing linearly. In this case, energy consumption per distance flown raises only as a square of airspeed.



In this plot we see that flying very light Pteryx at around 40km/h might give 25% efficiency advantage in totally calm weather with null windspeed at altitude, but because such thing never happens during daytime, differences between unloaded Pteryx and heaviest configuration with around 4m/s wind speed is almost null. Once again above around 7m/s it is no more beneficial to continue the mission with Pteryx Pro, with Pteryx Lite flight time and efficiency becoming very low requiring switching to manual mode and returning home imemdiately.

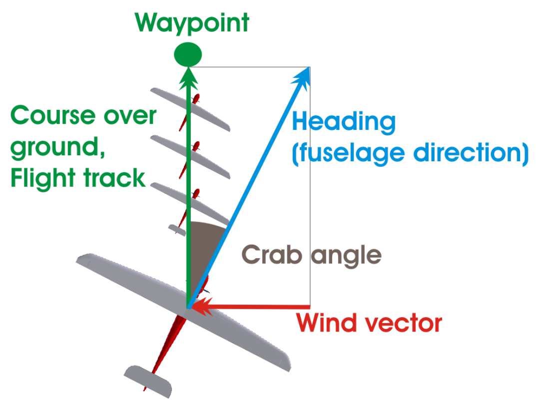
In both cases we see that a hypothetical system flying at 75km/h is largely immune to winds up to 10m/s, but is horribly inefficient for typical wind speeds when the turbulence is acceptable. i.e. in the region 0-6m/s.

Crab angle

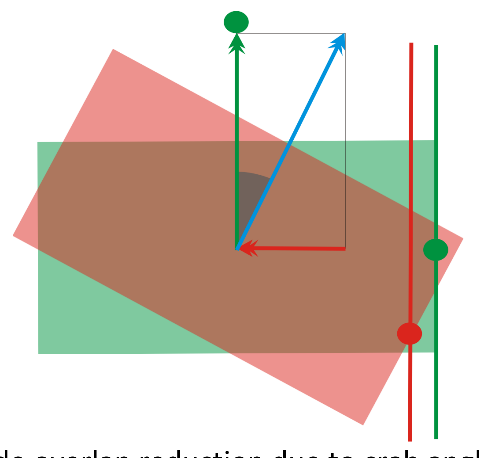
The crabs are nice animals that walk 'sideways' on their path. All winged aircrafts always do the same in order to maintain straight path over terrain. What is not intuitive from ground perspective is that winds at altitude never vanish and every platform in fact always tries to fly with its optimal speed into the air, the groundspeed and course being merely side-effect of air mass moving over terrain. The effect **affects not only all winged platforms, but also helicopters and multicopters**, since the latter also have the preferred direction in which they fly more efficiently.

Surprisingly, multicopters are never fully symmetric either, since even using counter-rotating propellers means one is working in propwash of the other, the upper propeller working typically in more favorable condition, even when the airflows equalize during hover the propwash of leading pair of propellers creates different lift conditions for the rear ones depending on combination of their turning directions. As a result even in quadcopters, once you have a platform that is fully mastered, measured and optimized, you still have a preferred direction of flying what is reflected in internals of the autopilot. **Deviating the optimal fuselage direction form flight path 'just enough, only minimally' to maintain course over ground is exactly the source of crab angle.**

In Pteryx UAV, there is a unique option of rotating the whole pattern automatically in flight, after a wind direction is detected overhead. However, it must be noted, the strategy works only for regular, almost-square patterns otherwise the area covered might change drastically. Rotating elongated shape is completely not an option, as the number of legs and time spent on turns rises dramatically, as shown before. **This option allows reducing crab angles to a few degrees, typically. In typical mission, however, one flies with a noticeable crab angle depending on wind direction that cannot be eliminated.**



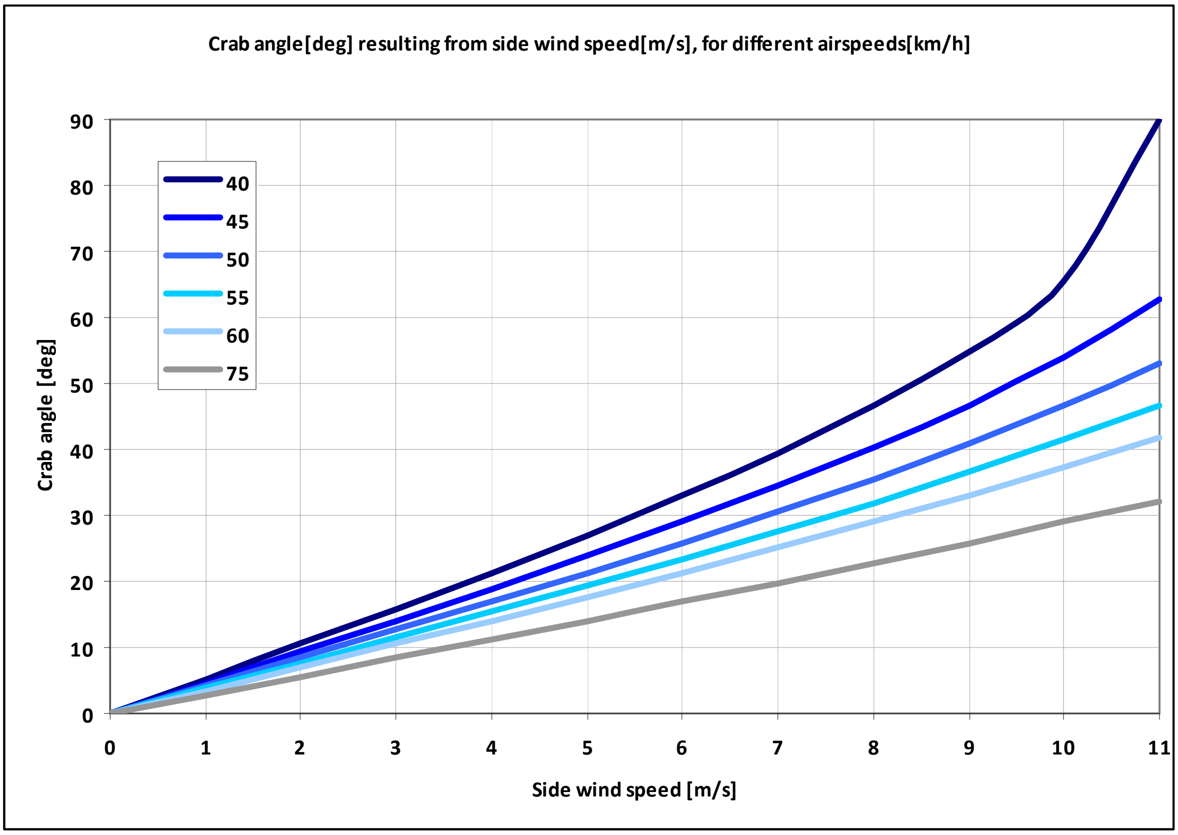
Worst-case example of crab angle: the wind blows from one side, exactly 90 degrees from desired flight path



Side overlap reduction due to crab angle. The width of photographed strip diminishes, reducing surface yield.
Along-overlap is similarly affected, mean photo with and height are reduced.

Before, we have analyzed the case when the wind blows along flight legs, what might prevent the mission from terminate successfully because of lack of energy. What happens when the fuselage is not exactly parallel to flight path and the camera is fixed to it? The photos are rotated.
This has two consequences:

- Pre-flight: the turned images mean that average width of photographed camera diminishes and in order to maintain the same side overlap required for processing software, one might be forced to diminish leg spacing in advance. Is it worth the effort? (NO)
- Post-flight: some image mosaicking software designed for ground work might have trouble mosaicking the data. Can it be eliminated? (NO)

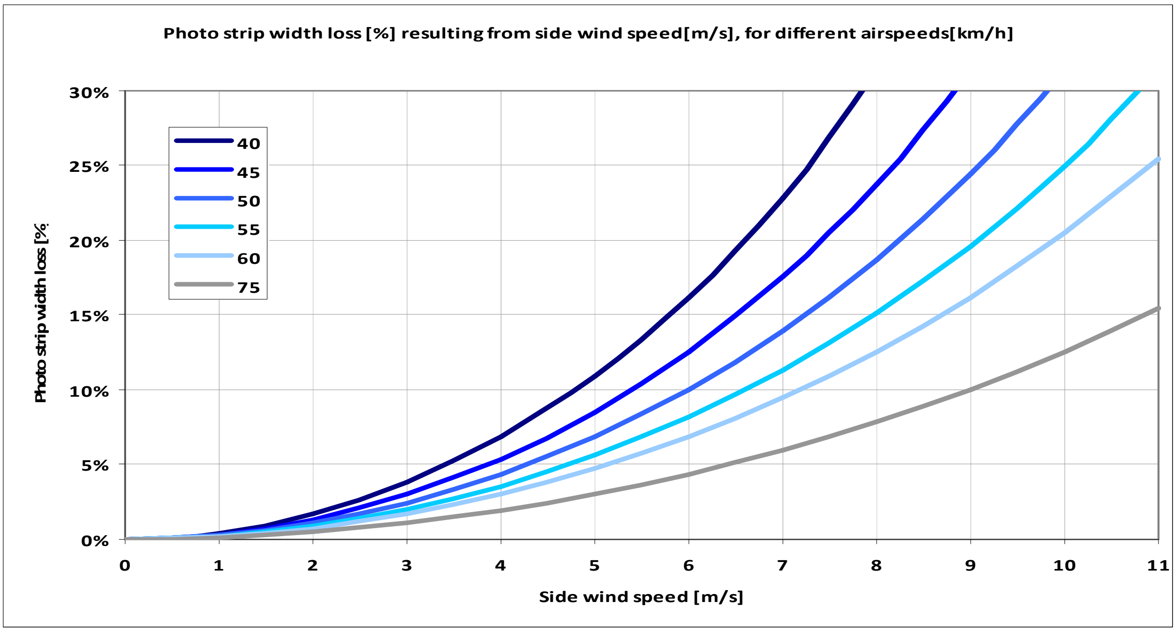


What we see that for operational wind speeds, the crab angle is never vanishing even for hypothetical, otherwise inefficiently fast, flying system. In fact **you can use the crab angle as visual indication that the wind speed is getting too strong and the plane will most likely not finish its mission because of lack of energy**.
For example, when you have a **Pteryx Lite** tuned at 40km/h and see a crab angle of **40deg**, you are sure the wind is **at least 7m/s**, or it could be more if the wind is not 90degrees to the programmed flight path. Obviously 40km/h is 11m/s, crab angle approaches 90deg for 11m/s wind speed and then the plane cannot advance along its flight path. At this point taking manual RC control and speeding up to 22m/s or deploying a parachute immediately is the safest option.
For **Pteryx Pro** with typical load at **50km/h**, **30deg** is the visual indication of approaching recommended safe usage limits (**7m/s**).
A hypothetical system flying at 75km/h still exhibits important 20deg crab angle in 7m/s side winds.

You cannot reduce crab angle to a few degrees in non-cooperating weather without using airplane that flies like a rocket (say 250-300km/h) and takes off/lands like a brick, with all consequences for reliability and endurance. As a result all UAV-compatible mosaicking systems are accepting wide range of crab angles, by design. This is not affecting the final map quality, but is a restriction on available processing methods.

The software made for real planes flying several times faster often omits this effect, being not easily adaptable to relatively slowly flying objects.

How it affects required mission time? Along-photo overlap is equally affected as side-overlap (rotating a photo reduces its average length and width); however there are ample margins on along-overlap thanks to high camera shooting rates. Side overlap, however, might need to be pre-adjusted in advance for worst case weather, if the effect is judged to be significant.



From the plot above we can deduce that in the worst case operational conditions, Pteryx Pro flying at **50km/h**, **7m/s** wind speed flying directly side to flight pattern, the loss of overlap is about **12%**.

For a hypothetical system flying at 75km/h the loss is still in the order of 7%.

Mathematically, in order to counter 12% overlap loss due to side-wind induced crab angle, you should diminish leg spacing by said 12%. This would result in 12% surface coverage per unit of time reduction. In practice, the margins of acceptance for overlap are wide:

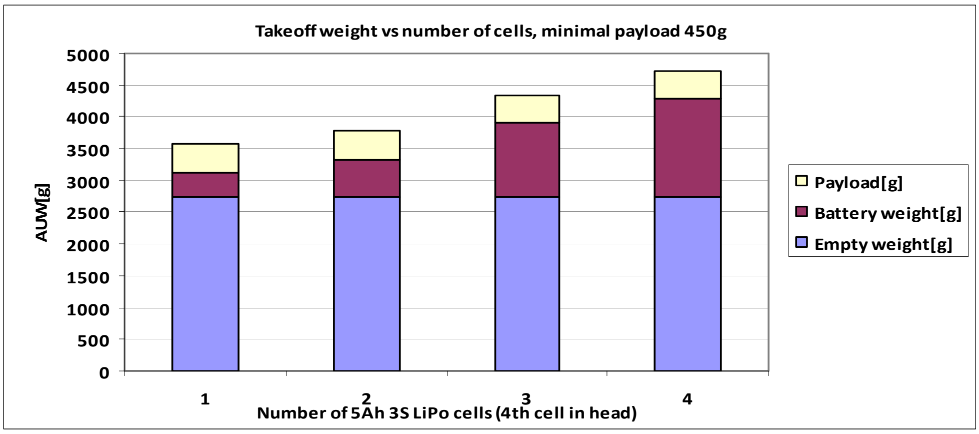
Suppose one requests 60% overlap, reduced by as much as 12% there is still 52% overlap remaining. If one requests 80% overlap, reduced by as much as 12% there is still 70% overlap remaining, all worst case. All this is not a problem for processing software we have tested.

Conclusion: crab angle has negligible impact on endurance due to flexibility of processing methods. We are not aware of any system adjusting the flight leg spacing because of side wind speed and we do not recommend doing so, as when needed, one can reduce crab angle in Pteryx UAV by turning the whole pattern in flight – if the area is a square.

A significant difference between overlap loss due to rolling plane and due to crab angle **i**s that crab angle produces quasi-constant, limited loss without localized map geometry degradation/distortion, while roll due to turbulence plus tight navigation has significantly larger range (can eliminate overlap completely) and has random nature. Therefore roll axis is stabilized while yaw axis doesn't have to be, what would lead to oversized fuselage and unreliable mechanics.

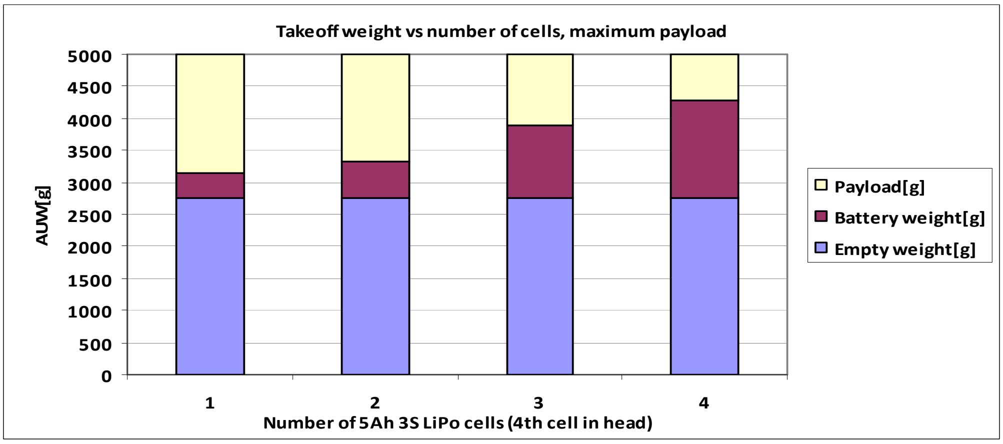
Battery count vs payload and endurance

In Pteryx Pro, you can fit up to 3 batteries under the wing and additional one in rotating head. The user has to paralellize LiPo 3S batteries, they come from different manufacturers, have different connectors (Pteryx uses Deans T-shape connectors). Batteries in the range of LiPo 3S 4.8Ah to 5.8Ah are available, pick brand name 20C ratings or budget 30C rating. When using single or double battery and max payload, brand name LiPo and 30C rating is required for comfortably safe takeoff thrust, also in manual mode. It is important to parallelize only batteries of the same internal resistance (same brand, make and if possible, same batch).
In Pteryx Lite, 2 batteries fit in belly and one optional in camera head. However Pteryx Lite takeoff weight from hand is 4kg and the empty weight is also smaller due to smaller belly, lack of tow hook, lack of buttons, and lack of parachute. Pteryx Lite data is not included in those plots but the endurance is roughly half of Pteryx Pro because of better gliding properties slightly catching up limited battery compartment and required small takeoff weight.
Trying to keep minimal payload and max endurance one has the following mass distribution:



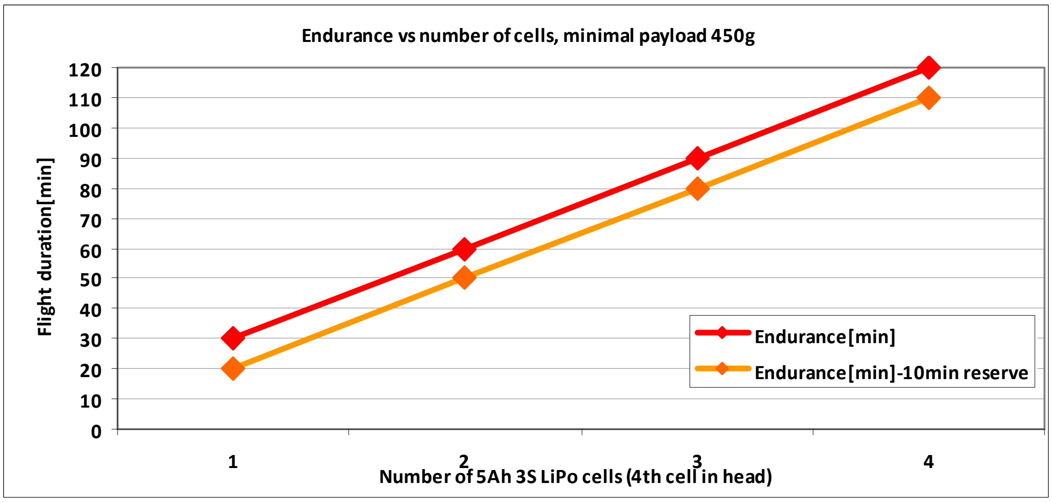
N cells	Battery capacity [Ah]	Empty weight[g]	Battery weight[g]	Payload[g]	AUW[g]
1	5	2750	383	450	3583
2	10	2750	575	450	3775
3	15	2750	1150	450	4350
4	20	2750	1533	450	4733

Using maximum takeoff weight one has the following mass distribution:

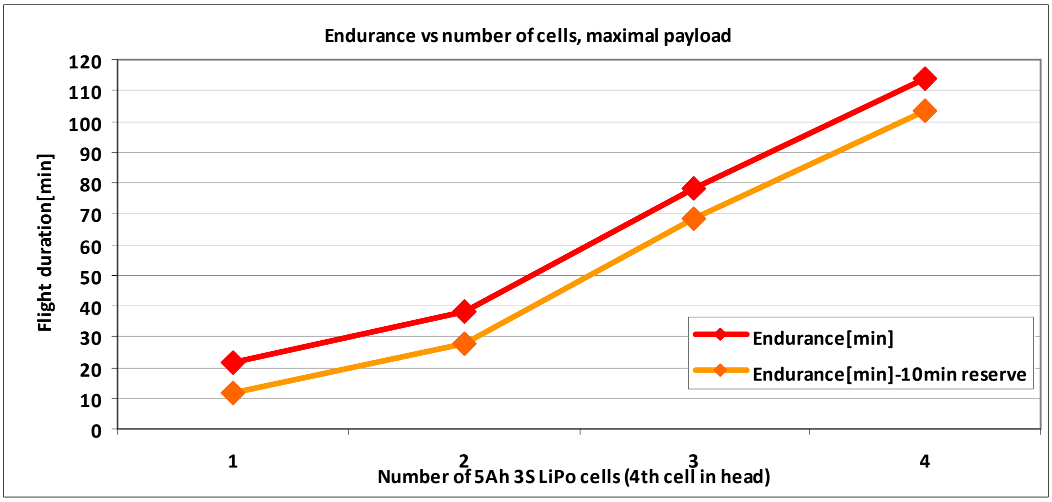


N cells	Battery capacity [Ah]	Empty weight[g]	Battery weight[g]	Payload[g]	AUW[g]
1	5	2750	383	1867	5000
2	10	2750	575	1675	5000
3	15	2750	1150	1100	5000
4	20	2750	1533	717	5000

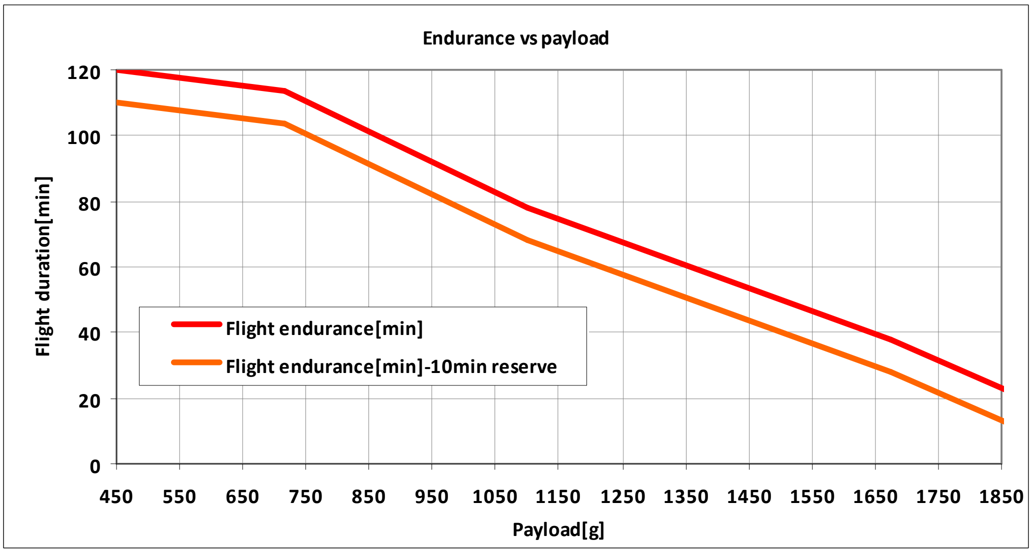
Experimentally found endurance figures for max endurance setup are:



For max payload setup, the endurance is limited:



In general, the following curve relates payload to endurance. Minimal payload is 450g because of the need to have proper center of gravity. This is more than single Pteryx Pro camera setup which weights around 280g. In general max useful payload is around 1kg.



Exceeding battery load is neither safe (difficult handling, less resistant to crash landing) nor beneficial (max flight time remains constant as wings operate in suboptimal conditions).

What if the motor stops working in the air

In general, nothing serious but one must have pre-planned action for that.

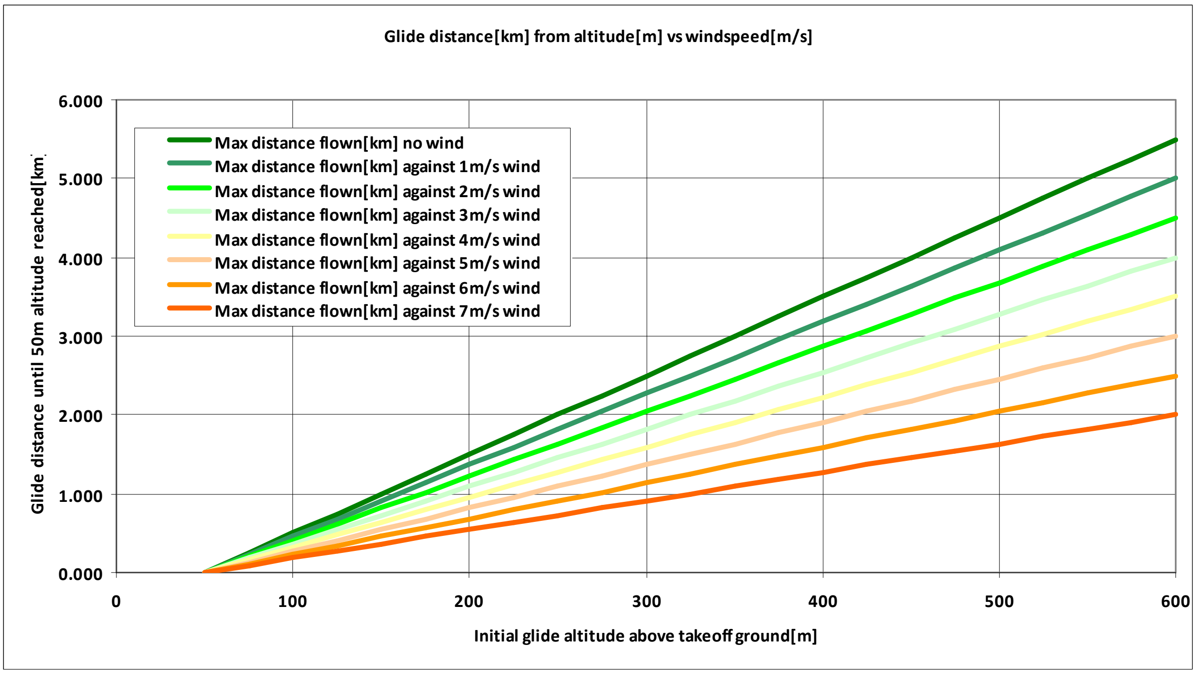
One must note that due to the fact the motor operates at 30-40% of its max power during flight, its lifespan counts into thousands of flying hours, probably much more. It is protected from dirt, requires no greasing and is probably the most robust element of the plane. This is a huge contrast to gas engines which require pre-storage maintenance, retuning before new season, checking after transport etc.

Atop of that, Pteryx electronic components have 200-300% power safety margins so the functioning of the propulsion is assured even in hot climate. Therefore in 100% of cases, **when motor stops working in the air it is because it has been ordered to do so, probably because of depleted battery.**

First of all, the system has a range of protections in the autopilot that direct the plane to takeoff position when the battery level is nearing to depleted. There are other protection logic like flight time, distances and various altitudes, all of them are custom and can be adjusted to reflect exactly user's mission profile and battery setup.
Finally, the autopilot cuts off the motor at extreme low voltage no matter the plane position but continue navigating. It will remain able to glide for another 2-8 hours. Moreover, after a few minutes of gliding, part of the battery energy restores and it is possible to use a few s bursts of throttle when landing in manual mode.
At that point it is still possible to take manual RC control, deploy the parachute at distance, or just wait until it glides home at lower altitude than usually.

When gliding one can assume 10:1 glide ratio, this is 1m altitude lost for every 10m flown. This is a pessimistic assumption for safety purposes. The figure is much worse that full-scale glider but not worse than best small scale RC gliders – the reason is the same as when explaining low rotorcraft efficiency, small relative size of flying surfaces compared to mean air particle distance. Pteryx layout is extending the safety using classic layout that provides good efficiency during both powered and unpowered flight. For example, flying wings when unpowered fly far from their optimal speed and have much worse efficiency.

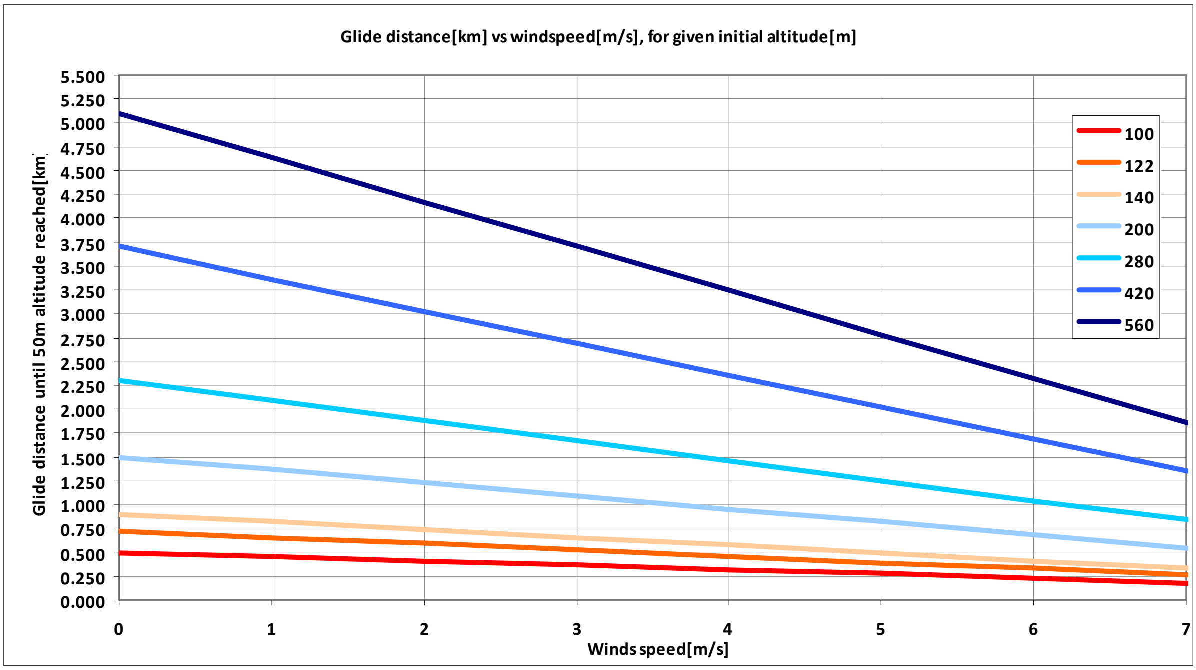
How high you need to fly in order to make sure the plane glides back if you know the wind speed at altitude?



It is clear that from below 200m altitude under strong wind, and even from 300m in exceptional cases, the 'maximum safety' mission radius must be limited or additional risk to be accepted. **We assume gliding until 50m altitude**; at that point one must prepare for manual landing (1-3 full turns remaining) or deploy the parachute immediately.

Additional reason for 50m limit: 30m is the height of many trees or constructions.

Even if they are not hit, they create severe local air turbulence and can obscure the plane.



Here we have selected typical altitudes corresponding to round ground pixel resolutions.

It is clear that the chase for the smallest pixel sometimes eliminates one backup chance of recovery (gliding home). The conclusion is that using automatic parachute deployment is necessary for long range high resolution missions. Pteryx battery failure recovery strategies are very safe compared to rotorcrafts or other less glide-capable platforms.

Flight safety

Active safety

- The pilot can deploy a parachute using old-fashioned and very reliable RC transmitter
- The autopilot can deploy the parachute by itself upon detecting serious anomaly or low altitude
- Manual flying as RC plane is possible and easy: special wing design prevents stalling; the plane is very agile for its size. Backup steering method is often requested by the laws, i.e. in Germany.

Passive safety

- Low kinetic energy: worst-case damage is limited and in par with smaller platforms, thanks to smaller flying speed
- Propeller configuration prevents impacting into target first, less breaking force; user's hands are far from propeller in all phases of takeoff.
- Stabilized head is controlled crash zone, sliding into the fuselage
- Wings are large but do not cut obstacles, they break from the fuselage dissipating energy into rotational motion and breaking the nylon screws
- Pitot tube never remains obscured by the rain, dust or bugs because there is none!
- The surfaces do not deform in the rain, the only wooden part is plastic-covered horizontal stabilizer; once the weather clears, there are no surprises during takeoff
- The plane is light, but relatively large. For good business return you really want to have a backup steering option, one that bypasses all things that might get wrong on communication channels, modems, laptop and event the autopilot. Manual RC control provides just that, and is using proven technology with 30-years operational history. But you must be able to tell plane orientation and distance from takeoff location.

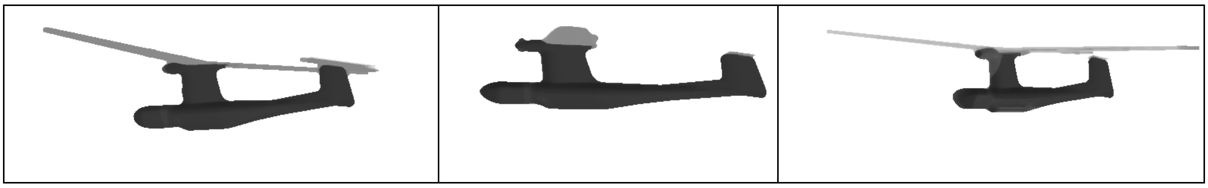
The absence of Pitot Tube, used for measuring airspeed, requires additional explanation. Contrary to intuition, the role of airspeed sensor in autopilots is not as much for controlling airspeed, but for assuring the orientation sensor can detect properly the horizon line. If Pitot Tube is obscured in flight in any way, or the connecting tubing fails, it is inevitable that during deep turn the plane will not be able to sense if the plane is spiraling down. Therefore a failure of this sensor is practically a guarantee of heavy crash if we let the plane loiter at some point of mission. This can occur during heavy rain, or a bug or dust can enter the tube making it one more failure point.

The autopilot used in Pteryx is a custom design which incorporates the airplane kinematic model, making Pitot Sensor not necessary for this platform. Knowing the risks associated with failure of such sensor inspired us to make extra effort on delivering you both the autopilot and the platform – with one less thing to worry about.

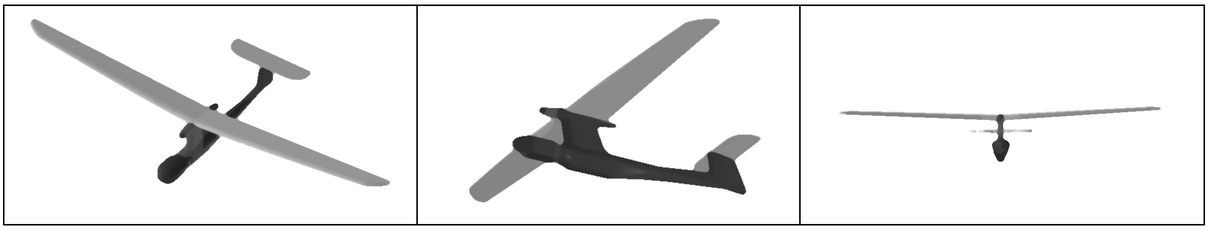
Visual identification

The plane is always darker than the sky (since the light source always passes the clouds from above) and is itself a low-contrast object. The difference between painting the plane in black and white is almost insignificant, while painting on bright and contrasted colors makes finding the plane in high grass much easier. White color is also preventing overheating the surfaces and preserves their geometry on the sun, is therefore preferred color in aviation. The major source of orientation for the RC pilot is plane shape and size.

Pteryx UAV has distinct shape that among other features supports vertical placement of RC transmitter antenna, extending the RC range, but also providing easy flight direction identification:

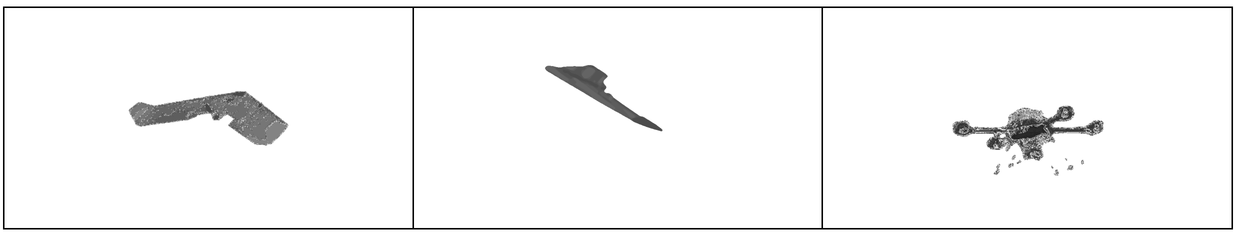


The sequence above is what the RC pilot is able to see at about 1km distance. It is hard to tell the difference with slightly outgoing flight and ingoing flight, as with all planes. The only solution is to have naturally stable plane that keeps flying straight and level once sticks are released, giving you time to guess flying direction what can take up to 5-10s of observation at extreme, emergency cases. Please note that identifying a quadcopter or flying wing in similar conditions would be completely impossible, therefore eliminating one more steering option.



The sequence above shows real advantage of Pteryx layout: you can tell quickly if a dangerous situation is developing because you can tell if the plane is flying up or down. When it falls for some reason, the fuselage becomes straight line giving a hint to open the parachute manually, or correct your manual flying.

For comparison, see two typical flying wing designs with 1m wingspan drawn in the same scale as Pteryx and large industrial quadcopter with similar payload but half the endurance. None of them offer fully manual recovery piloting mode at this distance and visual confirmation of their orientation is not possible without groundstation, despite being within visual range.



With Pteryx we have witnessed surprisingly good visual identification distances. We compare the experimental results for Pteryx UAV to extrapolated hypothetical 1m wingspan Pteryx, therefore assuming the same, ID-favorable shape. Note: the flight altitude is 300m, altitudes below 150m tend to produce ‘flat image’ impression and reduce flyable distance in manual mode.

Without additional spotter, immobile pilot/operator, 300m AGL, flat visual distances:

Object	Traceable distance	Comfortably flyable in assisted mode	Comfortably flyable in manual mode
Pteryx UAV, clear weather	1700m	1400m	1200m
Pteryx UAV, late afternoon, imperfect visibility	1200m	900m	600m
1m ‘nano-pteryx’, clear weather	600m	500m	430m
1m ‘nano-pteryx’, late afternoon, imperfect visibility	400m	350m	300m

It should be noted that using optical aid like binoculars is not really helpful in practice if the binoculars are not high-end, optically stabilized and do not have adjustable zoom, the reason is that one must find a reference point at small zoom then close-up and follow a small object with large zoom (there are no references on clear sky). Besides, the laws usually forbid using optical aid in determining visual range, what is compatible with operational practice. It is much more practical having secondary observer at edges of flying field that simply notifies the pilot in case of dangerous situation, in which case the pilot simply opens the parachute before a problem develops.

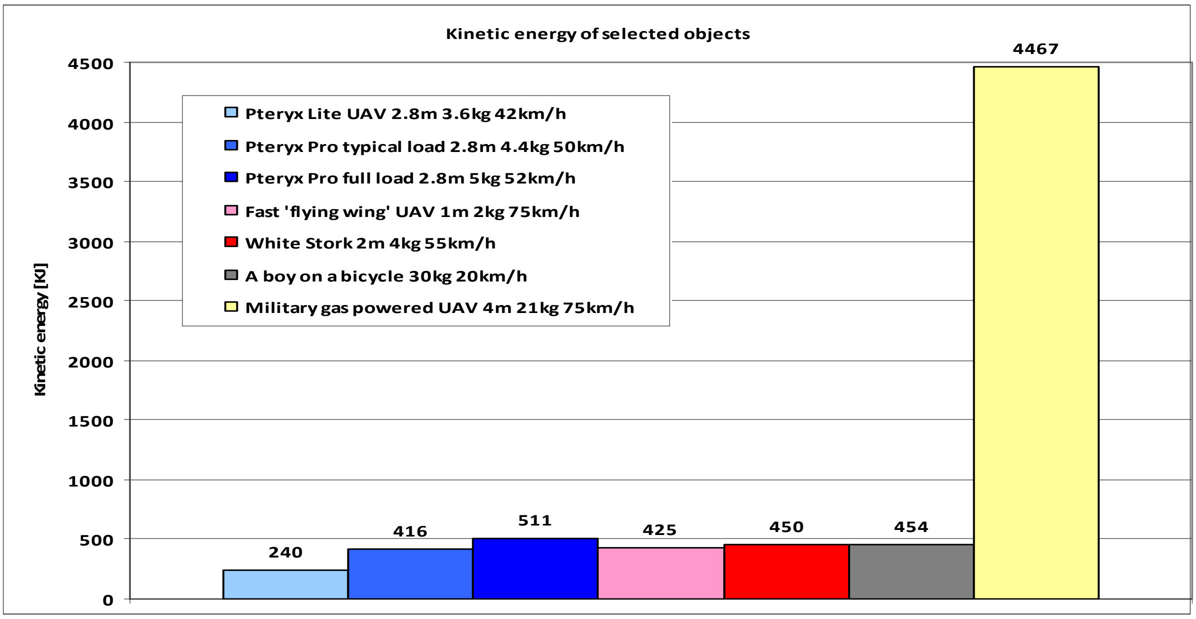
Conclusion:

Pteryx remains within visual range without moving the observer up to 1.7km away what allows flying 2.4x2.4km mission that yields well above 5km^2 map surface because of photo-margin around flight path.

With a single complementary observer and/or moving pilot, the UAV having a parachute, one can easily manage airspace separation up to 3-4km from takeoff point without much effort and without using a car for transport. It is possible to put the UAV in loiter at any given time using RC transmitter while the operator and observer transit to better spotting place, while mission termination logic is supervising remaining distance and endurance the whole time.

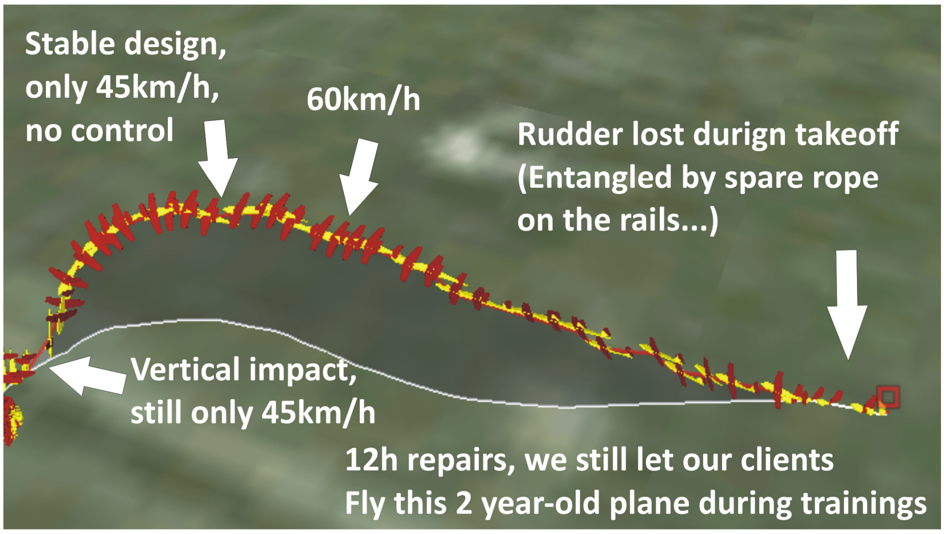
At worst case if you get lost in a bush, you will find your Pteryx Pro at takeoff position, parachuted.

Pteryx Lite would loiter around takeoff position until battery ends, then would glide down in shallow turn usually causing no major harm to anybody, but could become damaged if hits a tree.



Not only Pteryx UAV has similar kinetic energy to birds or smaller UAV, but its size means that upon impact components can start rotating motion dissipating the energy.

It has to be remembered that even the modest UAV can entangle in forward control lines of a paraglider leading it to stall and irrecoverable loss of altitude, which leads to the conclusion that all together: **manual flying capability, autopilot-assisted manual flying capability, operator not tied to the groundstation, easy visual identification and possibility to open parachute all form a set of options for non-registered air traffic avoidance**.

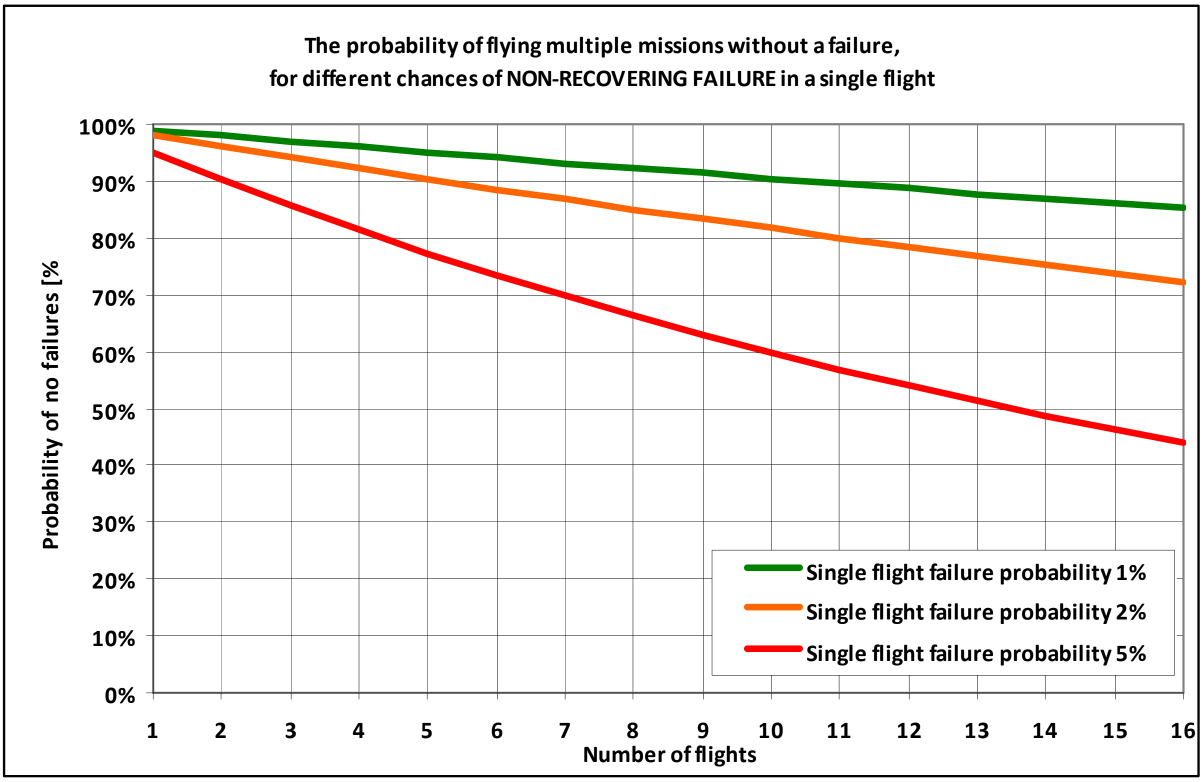


Pteryx UAV aerodynamic concept is highly self stabilizing and vertically asymmetric, meaning even if the most unthinkable damage occurs in flight, it never falls down like a bomb.
As a result the speed is not increasing dramatically.

Probability of successful campaign vs probability of small failures

Statistics often gives counter-intuitive results. Let's revise some theory and plot simulation results in order to answer the basic question: when it is good to fly several shorter missions ('the more I try, the more chances to win'?) or is it good to try to fly much larger missions.

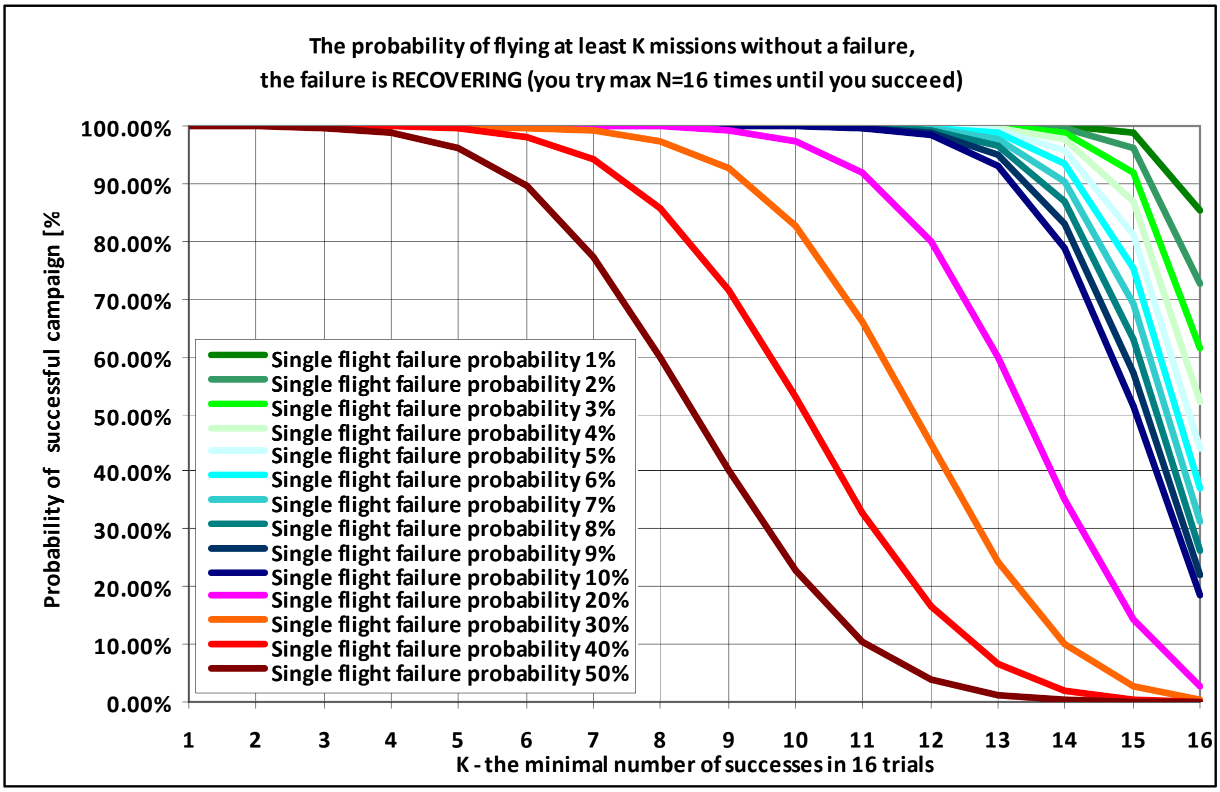
The first observation, also valid for full-scale aviation, is that most failures occur during takeoffs and landings. Indeed, at cruise altitude the plane uses fewer power, is far from the ground, the reception ranges are good. Landing, however, has some risks that are both small, difficult to assess but can build up quickly. Assume we have a small percent of a chance to fail: be it 1% failure because the plane can hit a stump or a large rock upon landing. Let's suppose this is not destructive for the system, but will cause a failure for the mission since it cannot be repaired in the field. The build-up of risks is the following:



It can be seen, that requirement to fly 16 missions in a row without failure is quite demanding. Let's say 1% chance of landing in narrow valley atop of the only building in the middle, repeated 16 times in a row gives only **85%** of not causing major mishap. If you have two buildings or twice that many trees, the campaign success rate melts to **72%**. If the chance of failure is 5% because the landing field is very rocky and you cannot make minor repairs in the field, you have more than **50%** of chances the plane will occur damage before completing the campaign.

CONCLUSION: Flying several small missions makes you very vulnerable to even most improbable mishaps requiring small repairs for which you are just not prepared in the field be it because you lack voltmeter, specific screwdriver and connector or if the glue requires a few hours to harden.

What is the situation when you know something happens periodically like clouds that will appear only on the photos once downloaded, and you have to discard the result then, yet the weather is changing all the time? Let's suppose you have booked a hotel for two days and want to fly with a system that could make 8 short missions each day.

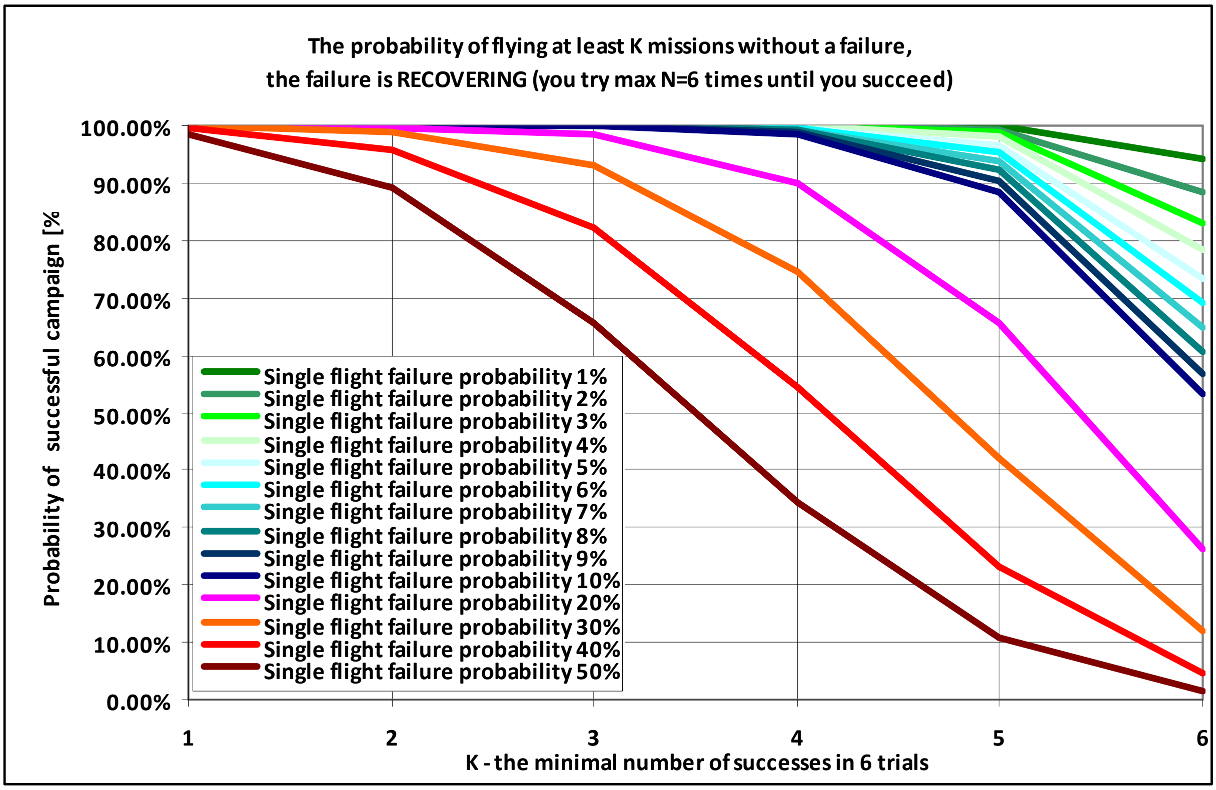


The first observation is that when the clouds appear only 3% of the time, you have only about 60% chances no mission will be wasted (16 successes in a row) and about 92% that you will have at least 15 good missions.

Things get worse when you know you got cloud cover 50% of the time but you expect half of the surface to be mapped. Unfortunately, the chance of succeeding 8 missions in 16 trials is only 60%. If you want to be 'sure' with say 97% chances to 'return home' with commercial results, you have to plan having only 5 missions. This is more pessimistic than guessing 'half of results will be good'.

CONCLUSION: You cannot handle uncooperative weather with good success rate by using simply many trials.

Similar case as before, this time we have a small system that gives us 6 opportunities per day, say 6 half-hour flights. Suppose you have to takeoff for a small place that is remote to mission area, but in order to get there, you have to overfly local club airfield. You have short window of opportunity and you can have go/no go permission once you are in the air. If not, you have to land to give way for the traffic.



Let's say it is enough to have 3 missions to succeed, once we did this in any order, we go home with the data. If you are given permission only with 50% of probability, surprisingly you have only **67%** chances to succeed.

Now imagine you have a larger UAV that can map the area that is 3 times larger in a single flight. First, you will get similar number of chances that is 6. Probability of bringing the data home is high as you need only 1 success. This is very close to **98%**.

Let's reformulate the problem: the camera dies in half of the cases as you discover in the field. It looks as it happens during takeoff, the failure probability is high, maybe something disconnects but once you are not shaking it – it works then. You can fly with small missions having said **67%** chance of success, 3 times not necessarily in a row.

Or just fly 2 large missions (each takes time slot required for 3 smaller missions). This time you get chance of failure per mission 50%, but the chance that both will fail is only 25%. This means with larger mission you still get comparable **75%** success rate.

CONCLUSION: For recovering and erratic failures that 'just happen', subdividing the problem into several missions is not increasing the reliability in any way, only brings probabilities closer to their theoretical limits of infinite number of tries. On the other hand it is easy to find real-life scenarios when flying long mission has high advantage over shorter missions. The fear of potential frustration 'what if I fly for two hours and it is useless afterwards' is unjustified. If you fail with long mission, you would fail with several smaller ones and this just means bad flight/business planning relying on luck.

Robustnes and materials

Pteryx construction is high-end fiberglass, significantly more durable than cheap fiberglass used in RC planes. It requires much less attention and minor repairs after each flight. Major crashes are limited by presence of parachute. Major crash presents a problem for every UAV as the autopilot is typically adjusted for specific geometry. This in turn requires experienced RC pilot for the first test-flight to teach the autopilot to fly, what requires simply trimming the plane at mid-throttle to fly straight in manual mode – if everything goes right as usual, what is not obvious after a heavy crash and refit. We make a test flight after a major refit, we also test fly (a few times if necessary) every new Pteryx Pro. Typical platform life is about 200 flights, but landing in manual mode on the meadow by experienced RC pilot allows robustness well into 1000 flights. Such intensity of operations is inaccessible for RC planes. Repairs of the smaller cracks in the fuselage are possible by the user using fiberglass from RC hobby shops, but are much less frequent than in RC models. Those repairs are not difficult as the fuselage interior is spacious and is easily accessible by brush, the inner surface having regular, porous structure.

As a rule there are no elements that can are using scotch tape or anything that can melt/slide in hot weather. The wings are made entirely of fiberglass with Styrofoam, making them completely resistant to water.

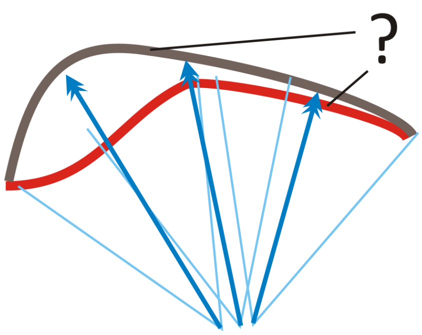
Resistant to water, to sun, but also resistant to low temperatures.

The reason for efficiency of winged platforms

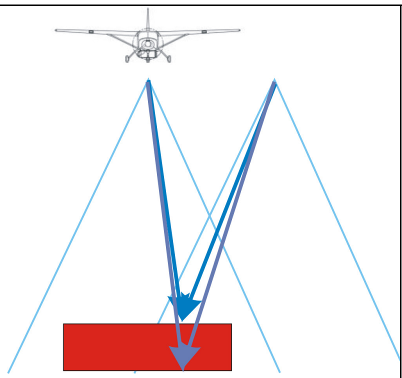
In general, winged platforms have larger moving surfaces relative to mean distance between air particles. Because of complexity and nonlinearity of properties of compressible fluids for small flying objects, rotor aircrafts have always worse efficiency for given amount of fuel and mass. This is particularly visible for small UAVs, where the difference of safe endurance per mass is about **half** for rotorcrafts compared to airplanes. The smaller and less elongated blades the worse is efficiency ratio.

Contrary to rotorcrafts, Pteryx returns gently with glide ratio of about 10:1 with all equipment installed. This means, from 300m altitude it can fly 3km with no wind, less in headwind, more with tailwind.
Pteryx Pro has also a parachute, therefore should low battery situation occur, Pteryx Pro will always return automatically but parachute will give extra comfort not forcing to land in manual mode with no second try option. As a consequence, safety margins are in the order of 10min of flight what amounts to 8-16% of flight time, as opposed to 30% commonly used in rotorcrafts (which cannot deploy parachute without entangling it).

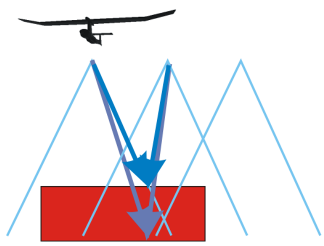
It is important to understand that the geometric information extracted from the photos requires moving parallel to the object, as opposed to shooting panoramas. Ability of rotorcrafts to hover and take multiple photos at given location adds nothing to reconstruction geometry, could only increase pixel count. This however can easily be achieved using 1kg of Pteryx payload and putting several compact cameras in the head, so once again being stationary at certain points in the air has no benefits.



Multiple photos from the same position yield no additional information about geometry. No extra depth information is gained from **stationary** quadcopter, helicopter, balloon, mast or kite.



Using aircraft for geometry reconstruction is good as differences in angle of view yield height information.



Using low flying UAV for geometry reconstruction is even better because relative angle differences due to height change are larger and the object is seen from many angles.

As seen above, alternative strategy to minimize distortion around high buildings or structures near to map edges, while staying concentrated on suburban areas is:
fly as high as permitted, deliberately diminishing legs spacing and accepting skewed buildings as skew angle diminishes with altitude.

Answers to FAQ

What is in the package and what has to be added in order to fly?

Pteryx Lite:

- UAV platform fully integrated with autopilot, stabilized camera head
- Without RC controller (country-specific, integrated by the user following autopilot instructions what involves setting up channels/mixers according to RC system manual)
- The user integrates mission payload (camera) of choice or any other payload

Pteryx Pro:

- UAV platform fully integrated with autopilot
- Stabilized camera head
- Towing hook, large belly and parachute bay
- Integrated with user-supplied RC and transmitter (again, country specific)
- Test-flown
- Takeoff rails and nails, bungee, rails carrying case
- UAV carrying case with space for RC transmitter
- A parachute

Both:

- The user supplies LiPo 3S batteries and chargers (any RC shop). The quantity depends on intensity of operations and required number of spares in the field.
- At office, a PC computer for mission simulation, USB printer cable.
- RC transmitter with PCM or 2.4GHz system, compatible with permissions in your country.
- A toolbox. Details in the section *Pteryx field tools*.
- On the field, having a Netbook allows downloading the logs and multiple flights if the memory is exceeded (the autopilot can be configured in such a way it can store 12h or more data at reduced rate and up to 8192 photo positions, that corresponds to 8h flight time, however we prefer to download after each flight as it documents any problems building up and makes data processing better organized)
- Extensive toolbox list, see next answer

What are test & maintenance tools and pilot's equipment required on the field?

Single mission equipment:

- Portable voltmeter, preferably pen style for diagnosing battery levels
- Hand-held hanging electronics scale, 20kg range (measuring takeoff weight (5kg) and static thrust (3kg), measuring bungee tension (10-12kg); it is ok to hang by vertical stabilizer)
- Flat screwdriver 6-10mm head width for unmounting stabilized head and attaching wings (may be very short like 6cm, it fits in the pocket)
- Pen and paper for taking notes about issues and mission details
- Hex key #3 (3mm) for propeller
- Spare car hood type screws, 10…12mm long (belly mounting, servo mounting)
- Sun protective glasses
- Anti-mosquito spray for more relaxed evening flying
- First aid kit against propeller-induced injuries or small cuts
- Extra rubber bands (6x1mm, 150mm circumference) for horizontal stabilizer
- Fiberglass-reinforced adhesive tape from RC shops, scissors
- Anemometer as the ultimate reference of no-go condition
- Stopwatch (may be already built in RC transmitter)
- WD40 spray, mostly for bungee rails but also for other applications
- Medium speed/density (15s) cyanoacrylate glue plus accelerator for quick fixes
- Spare wing screws and bolts (in case the originals are lost in the luggage)
- Use cheap portable camera for documenting takeoffs, this helps analyzing near misses for further analysis

Pteryx Pro only:

- 2kg hammer for bungee attachment
- 10mm camera wrench (mounting screw in camera base)
- 8mm wrench for takeoff hook

Multiple mission equipment extras:

- Netbook (choose max battery life, preferably more than 5h, scratch-proof case)
- USB-B (large) printer style cable, preferably in flexible silicon, more than 1.5m long becomes difficult to handle in the field
- Spare batteries (charging in the field is time consuming and destroys car battery
- because of full capacity cycling per day)

Pteryx Pro only:

- USB-B mini cable for camera
- Spare SD cards (more reliable than erasing in-place)

Spare camera batteries (the camera supplied lasts for 2h in full manual settings)

What is the data necessary for processing after the flight?

- Pictures on SD card of the camera
- Logs in the autopilot
- User input: time offset camera vs GPS or the number in filename of the first photo
- Optional: position of about 4-8 landmarks visible from the sky, preferably on ground level (use geodesic grade GPS if possible)

How do you match the photos from the camera to GPS positions?

High quality GPS enhanced with inertial navigation unit saves the positions in autopilot log along with UTC time of the event.

The camera records files under unique names with its own timestamp in EXIF data.

Pteryx software allows both strategies:

- match photos to event using filename which contains a number, the user provides the number of the first photo
- match photos to event using Creation timestamp from EXIF, the user must provide time offset between internal camera time and GPS UTC time in seconds (the software selects nearest match)

Is the output compatible with autopilot/system XYZ?

Pteryx uses custom high-end autopilot. While it is not emulating other designs, it produces all the data that is widely recognized by processing software. Standards like NMEA, GPX, CSV, EXIF tags, Google Earth KML and text outputs are the common denominator.

Besides, it always creates custom outputs for the most commonly used mosaicking software. Therefore it provides immediate replacement or complement in any existing UAV photography processing chain.

What is the output from the software included with UAV?

If the user provides time offset (camera vs GPS) and the list of photo filenames, the output is:

- Inflight black box autopilot data as Google Earth kml, csv
- Flight statistics and all emergency events as csv and txt
- Photos overlaid in kml for overlap preview
- Photo positions as gpx, NMEA csv formats
- Additional input data tested with major processing solutions:
    - Pix4D
    - Giscat
    - MosaicMill
    - PiEngineering
    - Areoscan
- Using free GeoSetter software with graphical interface, using the gpx/NMEA positions, one can update EXIF data in the images to contain photo positions

What is the time required to process the data?

All parameters for decoding the logs are constant, except camera time offset varying slightly each week.

- about 2-5 minutes to download all logs
- about 0.5-3 minutes to process the logs with supplied software
- about 15 minutes to verify photo overlap
- about 15 minutes to update EXIF data if necessary

(at this point the photos are **georeferenced** with about 5m positional error)

- up to 12 hours to upload the data to processing services (gigabytes)
- 0.5-24 hours of image stitching with external service or software
- 0.5-4 hours of data download (gigabytes)

(at this photos full **orthorectified and georeferenced** map and 3D model is available)

The process of rectification of naturally time consuming and requires the most powerful personal PC available. We advise using cluster processing services in order to reduce user's spending on infrastructure and processing staff.

How is mission planning done?

The autopilot in Pteryx Pro has around 30 preprogrammed missions which can be selected on the field using rotary connectors.

A few missions require entering target coordinates from the console connected via USB port, while most of the missions are patterns evaluated automatically relative to takeoff position; therefore no laptop is required in the field, as no keyboard has to be used. The UAV knows where it started moving thanks to its own propulsion and the mission begins, regardless on which continent you are!

Simple modifications of the mission like rotation can be entered from the console on the field if specific order of mapping is desired.

All missions can be reprogrammed to a customer-specific mission. There is Excel spreadsheet available that automatically optimizes space taken by waypoint memory, all the user has to do specify is overlap, flights speed, camera resolution, requested pixel resolution and map size; it is sufficient to copy-paste a produced table into the autopilot's console to update the family of missions.

This means you can arrive on the field equipped with not just plan B, but some 36 backup plans under each mission slot, previously planned and reviewed with Google Earth.

If somebody asks you to map one more field in the afternoon before you leave, you can switch to standard plan and takeoff a large mission near the middle of the bonus target; all this at 1 minute notice, when a laptop would be already low on battery and unavailable for time-consuming mission upload.

What camera is being used?

It is Canon S90 10MPIX camera. The camera shutter used and mounting supports many different cameras up to about 800-1000g. Possible other choices that can be installed by the customer are:

-dual Canon S90/S95/S100 installation
-a single Canon G9… G12 series
-certain models of Sony NEX like NEX3N, NEX5 etc
-low resolution Canon S series also tends to provide excellent pictures with reduced noise, the resolution that can be improved with lower flight altitude.

The cameras we propose are fit for the job; it is not advised to choose a camera based on ground shooting experience.

How does the camera operate?

The autopilot has camera shutter output that can be customized. It can support the following shuttering method:

-universal mount using mechanical lever using RC servo (*installed in Pteryx Pro*)
-IR shutter using the camera manufacturer's pilot
-TTL signal on the wires routed directly to modified camera trigger button
-modified USB connector and modified Canon with custom CHDK firmware

Several methods and their configuration are mentioned in autopilot manual available for our clients. The skills required are not different than for any other autopilot system.
Any activation of the mentioned system is logged in the memory of the autopilot together with timestamp, position and orientation data.

How many images it can take?
Assuming shooting images at maximum possible rate (we use it for having backup photos) Each 3.5s, supposing max flight time of 2h we have
2*3600/3.5=2058 max photos. Average mission is slightly less than thousand photos.

How robust is Pteryx?
Typical platform life is about 200 flights, but landing in manual mode on the meadow by experienced RC pilot allows robustness well into 1000 flights. Using the parachute during every landing lessens platform life in not easily quantifiable and somewhat random way, requires replacement of battery bay.

How precise it resulting ortophotomap?
Without using ground control points expect a few (1-5m) global map offset, sub-pixel global geometric accuracy with some 1-10 pixel local geometric distortions around tall objects. Global map offset drops to sub-pixel precision after introducing around 4-6 Control points measured with good quality geodesic GPS system. Major advantage, however, is more contrast and color definition of the map, each pixel carrying more information that with other technologies.

What are the dimensions and key Pteryx Pro specifications?

Span [m]	2,8
Length [m]	1,4
Height [m]	0,33
MTOW [kg]	5,0
Payload (without batteries) [kg]	0,45 – 1 *1
Endurance [min]	up to 120 *2
Cruise speed [km/h]	45-55

*1 1.5kg limited endurance, split payload outside head *2 depending on payload

What is the flight speed?
Around 50km/h=14m/s.

What is the maximum speed it can fly in?
7m/s at flight altitude, about 25km/h. The limit is not sharp, it is discussed earlier. The wind is associated with degraded photo quality and has impact on flight safety and business model. The choice is arbitrary but affects all small UAVs as the limitation is also linked to camera sensitivity/exposition time vs turbulence, associated with higher winds. This condition is not easily quantifiable as it depends on terrain and topology of mapped region.

Do you supply Ground Control Station?

No. Our mapping experience shows it is not needed as it distracts the user for observing the plane, while it decreases overall situational awareness (visual contact is also required by the law). Every decision taken by the pilot observing the GCS is taken by the autopilot automatically. An anomaly that is severe enough to require human intervention is not feasible using GCS because of low update rate of long range modems, while the required data refresh rate for manual control is around 25-50Hz (similar to TV update rate). Having onboard video is not solving the problem as in practice it is one of the weakest elements due to weight, power consumption and interference sensitivity, while providing yet another very exotic perspective with narrow field of view, still, making practical navigation over *unknown* terrain almost impossible. Ground stations with extensive data display are impossible to read during mildest sunlight and are popular mostly because all autopilots designed for UAV research require them. For mature systems, the simple mission return decisions are taken more reliably by automated onboard electronics as they can take more inter-related variables into account. At the same time changing flight plan made of about 100 points in the air is impractical flying typical mapping mission. Variables like flight altitudes are dependent mainly on customer requirement (the higher the better for yield, resolution and laws being the limit), therefore are changed once per month at best. As a final note, having a groundstation in practice requires full-time presence of two highly trained persons during the whole flight, since diverting one's eyes to the groundstation is dramatically changing the perspective leaving the plane visually unattended, while reverse transition might be impossible if anything is different than usual or the plane is simply a small dot on the sky.

Can I buy spare parts?

Yes, we offer a range of spare parts that are custom built by us; this includes wings and all elements.

Some elements are trivial to be replaced by RC modeler, like horizontal stabilizer.

We also offer fuselage refit which includes replacing all servos, testing the autopilot and changing the fuselage. Due to complexity this requires final test flight, which we perform.

Summing it up all together

Pteryx design has been dictated by making compatible best practices and existing heterogeneous laws. The technology bent to match providing you with options to continue business for years to come.

- When you are forced to fly low, you need surprisingly high endurance to satisfy photo overlap. Pteryx provides that.
- When you are forced to fly low and close, you have low time to ground and still need a parachute. Pteryx Pro has that capability.
- There are operational limits from wind speed, Pteryx layout fits into them following extensive analysis of the real conditions and five years of trials with alternative platforms.
- Once the laws evolve requiring a transponder, you have both payload to lift it up or low kinetic energy to fit among the smallest UAVs.
- Mechanical simplicity with sophisticated electronics, self diagnosing and preventing small mishaps instead of accepting continuous wear for the illusion of easy replacement.
- Autopilot, platform and choice of components made for the civilian mapping task, instead of migrating laptop-centric approach from military and research systems.
- The interdependence of available parameters is enormous and has counter-intuitive consequences, therefore we have made sure the best aeronautics engineers worked on the project.

Final word

Pteryx operations can yield higher quality photos than existing systems, or can work in situations when noisy aircraft operation is forbidden or risky.
Main limiting factor is wind and associated turbulence, which has been addressed without compromises to the point here no further ‘simple’ improvements are possible, because we must stay within reasonable weight and airspeed allowing us to operate from unprepared sites anywhere in the country.
It has been shown that all aspects, advantages but also limitations of existing cameras have been analyzed and used to create outstanding quality maps within widest operational margins possible.
Precise analysis of business requirements can be made using the charts presented, showing opportunities and flexibility of the system to create various map surfaces and map resolutions.