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EXPLOITING METEOROLOGY TO ENHANCE THE EFFICIENCY AND SAFETY OF UAV OPERATIONS

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Vidar, SEVALDRUD Thomas

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8) ABSTRACT <p>The meteorological and topographical conditions in Norway (and in many other parts of the World) represent severe challenges for UAV operations. However, these conditions also provide opportunities that can be exploited to improve performance and safety.</p> <p>Aircraft can gain energy by using up-winds, and conserve energy by avoiding headwinds, strong turbulence and sinking air. The main atmospheric energy sources that are discussed in this report are slope wind, thermals and mountain lee-waves. Slope lift effects occur at low level, thermals are found from ground level up to intermediate altitude levels, whereas mountain lee waves occur from intermediate levels up to extreme altitudes. UAVs may use these energy sources to fly great distances, and to remain airborne for long durations without the use of engine power.</p> <p>It is suggested to use advanced atmospheric and topographic models, practical sailplane pilot experience and flight track logs to develop unmanned soaring capabilities. A UAV simulator will utilise prediction models for wind, up-lift, downdrafts and turbulence fields for flight path optimisation. This will enable more energy efficient and safe UAV operations. Sensor or other payload use may also be improved by the availability of more detailed weather predictions.</p> <p>A "Soaring UAV" concept is presented, with an airframe type that can effectively benefit from the atmospheric energy sources mentioned above. Several designs, following the same basic layout, with maximum take-off weight between 25 kg and 750 kg are envisaged.</p>				
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EXPLOITING METEOROLOGY TO ENHANCE THE EFFICIENCY AND SAFETY OF UAV OPERATIONS

1 INTRODUCTION

Unmanned aerial vehicles will probably enter into the Norwegian armed forces within the next few years. This happens as the UAV industry is growing and changing rapidly, gaining civilian and military user groups all over the world. Operational concepts, platforms, control systems and information technology are evolving rapidly. There is much room for new ideas in the years to come, within both use and design of UAVs.

This report presents ideas on ways to achieve more efficient and safe use of existing aircraft systems. A design concept for a new type of UAV called a “Soaring UAV”, or SUAV, is also presented. The ideas take advantage of recent developments in fine-scale meteorological modeling and aerodynamics.

1.1 Weather as a challenge

Harsh weather is proving to be one of the most important causes of failed missions and degraded performance for UAVs. The lack of de-icing capability and the low airspeed of most small or “tactical” UAVs are important problems. Other problems are cloud cover, haze etc., that cause degraded sensor data and varying electromagnetic propagation conditions (e.g. ducting).

Unmanned aerial vehicles (as well as most other aircraft) are typically flown in straight lines between predefined waypoints, or they fly defined search or loitering patterns. Flight plans are based on mission requirements, threats and airspace restrictions. Only a very general weather forecast is consulted (or available) when laying flight plans.

Without proper knowledge of atmospheric phenomena, operating UAVs is subject to a considerable element of uncertainty. Performance and safety in “the real world” is often much poorer than expected.

All-weather capability is an obvious desire for any UAV operator. Ideally, platforms and their payload products should be available at any time, as dictated by the operations they support. Most UAV systems are far from achieving this goal. UAVs are all too often grounded due to bad weather, or they are unable to provide useful sensor data.

Meteorological and topographical conditions in Norway (and many other regions) will pose severe problems for UAV operations if continuous availability is required. Strong wind, extreme turbulence, rain, hail, snow, icing etc. are well known problems. Such common atmospheric conditions may often drastically reduce aircraft performance and safety.

The ability to operate efficiently in both familiar and unfamiliar geographical locations is important. An experienced UAV-operator (or pilot in general) may be able to adapt well to the conditions “at home”, but cannot be expected to do as well when operating in unfamiliar locations without a long time to build experience. Many UAV-operators may not be highly experienced pilots (especially true for small UAV types), which is often a “selling point” emphasised by manufacturers. Additionally, an increasing level of autonomy in the future and multiple aircraft configurations prohibit the detailed planning and overseeing of every aircraft. Automatic (or autonomous) systems for “smart” and efficient flight in challenging weather should therefore be developed.

1.2 Weather as an opportunity – a proposed new concept

By exploiting high-resolution meteorological computer modeling and sailplane flying know-how, aircraft of any kind, and UAVs in particular, may achieve performance levels that considerably exceed those of current systems, with the added benefit of increased flight safety and active stealth. “Bad weather” can sometimes be turned to advantage, and each platform can be used more efficiently. This report suggests a way toward the implementation of such a capability in unmanned aerial vehicles.

It is desirable to utilise rising air and tailwinds, while avoiding sinking air, turbulence and headwinds. Sailplane pilots have taken this to the extreme. Pilots of powered aircraft do so to a lesser degree. This may be due to the rigidity of airspace management and time schedules, abundant engine power, sufficient fuel capacity, low availability of detailed meteorological forecasts and also a lack of awareness of the opportunities.

Forecasts based on state-of-the-art computer models may enable performance improvements that practical and qualitative experience cannot produce. Still, implementing practical sailplane methods and experience will bring potential benefits, even while using existing low resolution forecast services.

The concept that is proposed in this report can be summarized as follows:

1. Predict and utilise (as mission allows) atmospheric lift and tailwinds to extend range, endurance and altitude potential.
2. Predict and avoid (as mission allows) areas of sinking air, strong turbulence, headwinds, precipitation and icing danger.
3. Predict and adapt to conditions that influence payload and communications system performance.
4. Implement these capabilities in simulation and planning systems, autopilot software and platform hardware.

The potential of the proposed concept is unknown, as it appears that no UAV operator or developer has attempted to realise it yet. The core of the work proposed consists of theoretical,

programming and simulation work, and is considered to be low risk, with high probability of operational gains at low cost. More advanced unmanned soaring flight requires practical experimentation and development or adaptation of both hardware and software. The risks are higher, but the potential gains are great.

1.3 Sources of energy for flight

From Norwegian airfields, high-performance sailplanes have exceeded 1000 km distance, 10 km altitude, and 10 hours endurance without the use of engine power. Long-distance flights are accomplished by flying slowly or circling in up-winds, and by cruising at the optimal speed between up-wind areas.

Rising air is associated with a number of phenomena. This work will focus mainly on mountain waves, slope wind and thermals, which are commonly exploited by sailplane pilots. Depending on its aerodynamic performance, a UAV may also utilise these energy sources. Indeed, unmanned aircraft are in principle able to exploit an even wider range of conditions than manned aircraft, as they are subject to less safety and manoeuvring constraints.

1.4 Operational use of the proposed concept

Military UAVs are subject to varying mission restrictions. Some mission types will allow for more flexibility than others. It would be a great advantage to be able to exploit lift phenomena, avoid the strongest headwinds etc. within these mission restrictions.

Often a shift in flight path of a few hundred meters or less will be sufficient to e.g. increase ground speed and fuel efficiency and to avoid dangerous turbulence or sensor-obstructing clouds. The added performance and mission success rates may be considerable. It is not unrealistic to expect several hours extended endurance by implementing new features in planning, flight optimisation and platform systems.

Communications relay and loitering surveillance missions will often allow for great flexibility in flight path. In those types of missions, the goal should be to save a fuel reserve for as long as possible, and get the most mission-valuable time out of each platform. Time spent in transit is not mission-valuable, and should be a small fraction of the total mission time. Also, the number of platforms needed to perform continuous surveillance depends to considerable extent on the endurance of each platform. Longer endurance thus improves the cost-effectiveness of each platform purchased, as well as reduces the number of platforms needed.

The discussed methodology may be taken into account early in the planning process – in airspace management as well as single platform flight planning. In this way, the individual platforms will be given airspace according to their performance potential and limitations as well as their mission constraints.

Soaring capability gives the potential benefit of low observability (low thermal and sound signature) as well, flying with engine idling or stopped, and possibly very close to the terrain (evading radar). Low “stealthy” flight may additionally allow for greater probability of useful data (due to ability to fly below clouds) from low cost, lightweight sensors.

Availability of improved meteorological models may increase the capability to predict atmospheric ducting of electromagnetic energy. This may be used to avoid or postpone radar detection, or to optimise communications system performance.

No aircraft operations are completely deterministic. Better meteorological models will increase the likelihood of running into more favourable than unfavourable conditions during a mission, thus on average increasing performance compared with current operations. Any conditions that can increase performance within mission constraints should be exploited. This performance increase may be realized in the form of e.g. increased payload weight, endurance, range or altitude.

2 FLYING ON ATMOSPHERIC ENERGY

2.1 Slope soaring

Slope soaring (German: Hangflug) was historically the first way to gain or maintain altitude without engine power. The early pioneers of flight (Otto Lilienthal, the Wright brothers etc.) used slope wind for lift until engines became sufficiently light and powerful. Slope lift occurs when horizontally moving air (wind) is forced upwards by an obstacle (e.g. the slope, or hill). Depending on the shape and smoothness of the slope and on the wind speed, eddies and vortices may form on the leeward side (sometimes also the windward side). In front of and above the hillcrest it is usually turbulence free and safe to soar.

2.1.1 Manned aircraft

Slope wind can be used both to maintain position (horizontally and vertically) and to traverse great distances along ridges. This source of lift was used for setting the endurance records (about 58 hours) until the pursuit of such records were abandoned in favour of distance, speed and altitude record attempts.

Slope soaring is the most predictable of the three types of soaring (slope, wave, thermal). All that is required is wind and hilly terrain. Slope lift enables long-distance and long-endurance flights along ridges all year round.

Slope soaring is most often used as a last resort when there are no other sources of lift. However, experienced pilots have flown long distances along Norwegian valleys, making their way back to home base, hours after sunset. The close proximity to the ground makes this sort of soaring less forgiving of pilot error.

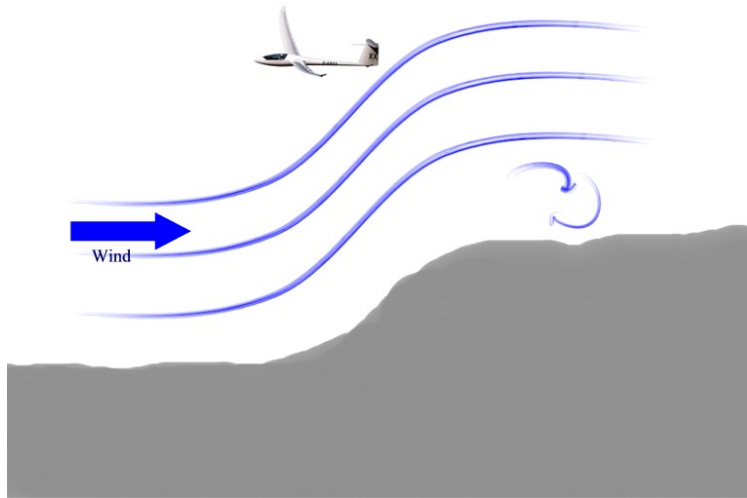


Figure 2.1 The slope soaring concept.

2.1.2 Unmanned aircraft

Slope soaring offers UAVs the ability to fly long distances or loiter close to the ground, silently, potentially undetectable by radar. A UAV flying silently, from below hillcrest level to 500 m above a ridge at night may be very hard to detect. A UAV can slope soar at night, within cloud cover and in conditions that are considered too dangerous (turbulent etc.) for manned aircraft. Fine scale modeling may reveal where dangerous turbulence and the strongest lift is most likely to occur, thus enabling a UAV to exploit very strong lift and avoid danger-areas. Advanced atmospheric modeling is not an absolute requirement, though. A detailed terrain model, general wind direction and sensor input (for speed/climb rate/position/attitude) are essential.

The ground proximity requires very accurate position control, of course. For manned or radio controlled slope soaring this is accomplished visually. UAVs must apply another solution. For anything but very smooth ridges, a very accurate terrain model and position fix is a must. Exactly how accurate the position fix and terrain model must be is a subject for further studies, but the more accurate, the better. An accuracy of a few meters allows for very low flight. “Non-jammable” solutions would be preferable, as orientation and navigation under all conditions are critical factors for safe and efficient flight. GPS (Global Positioning System) can be jammed or unavailable for other reasons. Backup position references should be considered, e.g. by combination of INS, ground proximity sensor (e.g. laser or radar) etc. .

A search algorithm will be followed to find the optimum flight condition (position, heading and airspeed), using the terrain model to avoid the ground. High quality model predictions will minimise time and fuel spent on in-flight path optimisation (e.g. using onboard sensors).

Propulsion assistance will be required to get across areas of missing or unpredictable upwind, and prevent altitude loss or crash landings. Propulsion assistance will also make it possible to venture slope soaring with weaker winds. Engine response must be rapid, and operators on the ground will have little time to react if things go wrong. Control should therefore be automatic to the greatest possible extent.

2.1.3 Development strategy

Following computer simulation, there will be a need for field-testing. This implies a demonstrator platform of some kind. The safety margin needed when using manned aircraft will narrow the envelope (wind and altitude range) that can be explored. It is therefore suggested that small motor-assisted unmanned aircraft (wing span 3-5 meters) should be used.

As a first step towards automated flight, the aircraft may be equipped with a video camera, position and attitude sensors, where the signals are continuously transferred by telemetry link to the ground control station. The ground control station runs the topography/atmospheric model, navigation and mission planning software. An autopilot may suggest flight control actions to an operator, and the actual control is via a standard R/C transmitter. Thus the pilot is in full control at all times, being able to reject or accept suggestions made by the autopilot. Using this setup, crashes will be easy to avoid and relatively inexpensive if they cannot be avoided due to e.g. malfunctions. Standard RC-equipment and electronics (properly protected) will survive a crash at low speed.

The next step may be to transfer the computing capability and autopilot into the aircraft itself. With greater confidence in algorithms and hardware, the aircraft may fly further (out of range of conventional RC-equipment, although RC control may be passed along a ridge for test/development), giving greater potential for testing in varying terrain and wind conditions. A low rate data link (e.g. Inmarsat) for submitting commands and receiving position and other status data will suffice, even though live video will be desirable to see what is going on. Such operation may be acceptable to civil aviation authorities when performed at low altitude, and well away from populated areas.

2.2 Thermal Soaring

The subject of thermal convection (rising air that is warm relative to the surrounding air) is more complex than slope wind. In summertime over both flat land and mountains, thermals form and rise, often manifest by cumulus clouds.

The altitude that thermal convection reaches varies from a few hundred meters to more than ten kilometres. Thermals involve turbulent mixing. Especially around the edges of a large and strong convective cell, which is often associated with thunderclouds, the turbulence can be quite powerful. Thermals are usually from a few hundred meters to a kilometre or so across. Updraft velocities may reach 30 m/s inside cumulonimbus, but 1-5 m/s is more common underneath and inside cumulus clouds. Precipitating clouds may give strong downdraughts.

On a sunny summer day, cloud base is typically between 1500m and 2500m above ground level, with cloud top at 3000 to 5000m depending on conditions.

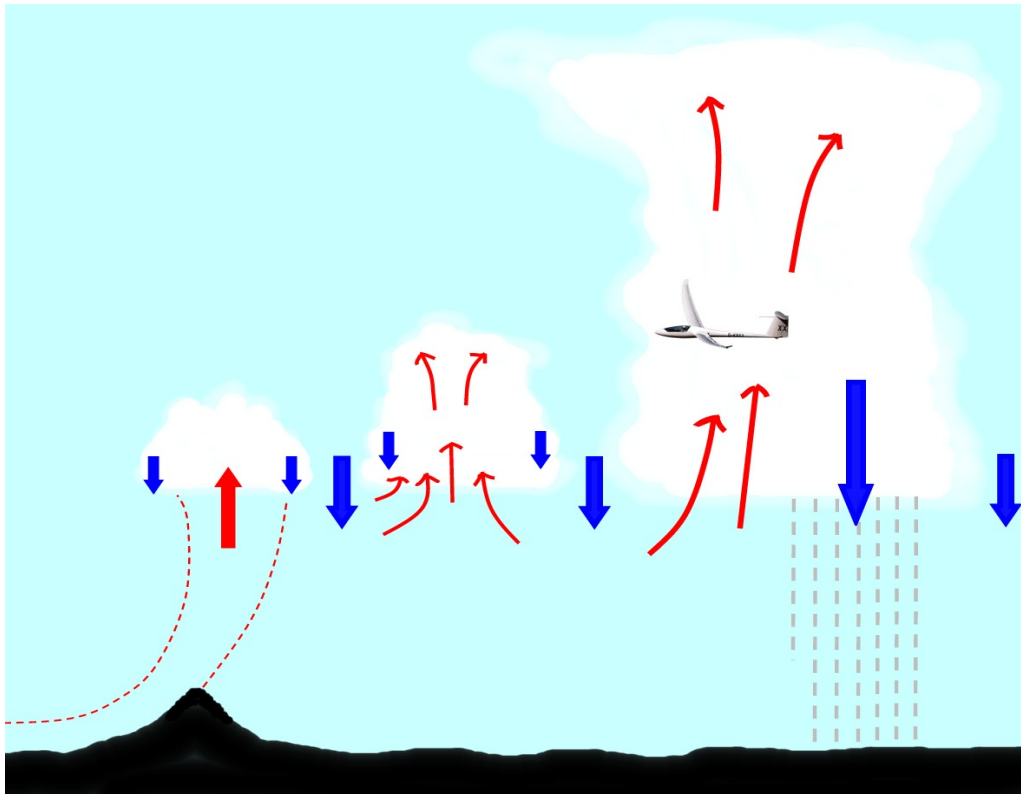


Figure 2.2 Thermal convection in different stages of development. At the far left, a thermal has just been formed, and the cell is being fed with warm rising air from the mountainside. In the middle sketch, a thermal has been separated from its source on the surface. On the right, a thermal has developed into a large cloud (a cumulonimbus), possibly a thundercloud with precipitation, and both powerful up- and downdraughts.

2.2.1 Manned aircraft

Most sailplane cross-country flights are made flying from thermal to thermal. Experienced pilots are able to predict where thermals are likely to occur by evaluating the ground conditions, solar position, cloud conditions, and the wind. In southern Norway and Sweden, flights of more than 1000 km have been accomplished, with average travel speeds of about 100 km/hr. In central Europe, even 1500 km (Lübeck-Biarritz) has been flown, mainly using thermals.

Sailplane pilots will typically fly within a working altitude range between 500 m above ground and up to cloud base. The “stochastic” nature of thermals makes them rather unpredictable, and it requires an experienced pilot to find them (and a little luck). Although experienced pilots are able to predict the most probable locations of thermals, finding them involves a certain degree of trial and error. However, once encountered, thermals are readily exploited by using accurate variometer (rate of climb) instruments. At a distance, thermals are best identified by the presence of cumulus clouds, and an evaluation of their shape and colour.

Once a thermal is found, the aircraft will be flown in a sharply banked curve, attempting to find the centre of the thermal where the climb rate is usually the highest.

Usually thermal activity stops a couple of hours before sunset. But heated rock, woods, cities and bodies of water may provide convecting air well into the evening because of their high heat capacity. These places should be avoided by soaring aircraft during early daytime (because they are slow to heat up, and therefore are most often accompanied by sinking air), but can be good for evening soaring.

Cumulus will often form long rows or “cloud streets”. Flying along these allows high travel speeds over long distances (often on the order of 100 km). Given a vertical wind shear (wind speed changes with altitude), a wave or “slope wind” may be found above the clouds.

Other heat sources, such as forest fires, industrial plumes etc. may also generate thermals. The drawback of such sources of lift is that they most often give off smoke, which reduces visibility.

2.2.2 Unmanned aircraft

UAVs are not dependent on visibility to fly safely and will probably be flying more inside the cumulus clouds than underneath them (depends on payload sensitivity to clouds). Many occurrences of so-called “bad soaring conditions”(the term refers to either lack of convection, convection with precipitation (possibly cumulonimbus) or no visibility) will in fact be quite favourable for UAVs.

Leaving a thermal at cloud base would be wasting energy for a UAV. Depending on temperature and humidity (icing conditions) unmanned thermal soaring has great advantages over manned VFR (Visual Flight Rules) flight in the option to fly several km up inside clouds. The UAV will follow strong thermals to the cloud top before starting straight-line cruise. A de-icing system may be required to fully exploit thermal soaring to its full potential. Leaving the clouds at top level may give a very good range for finding the next thermal before it is required to start the engine to maintain a safe minimum altitude. A very large cumulus cloud (a thunder cloud) may reach as high as 10km (the top of the Troposphere). Given a lift/drag of 30 (realistic for a high-performance UAV of medium size), the aircraft may glide as far as 300 km before the engine must be used, a distance it would take about three hours to cover when gliding. Using three more “normal-size” thermals would give the same three hours extra endurance. This will frequently be possible during late spring, summer and early autumn seasons in many parts of the World including Norway.

Once a thermal has been located, the aircraft should follow an algorithm to seek the strongest lift. Sharp turn-rates and heavy turbulence must be endured, so a soaring UAV should be structurally strong.

For identification of thermals, cameras (coupled with pattern recognition software) may be used for spotting clouds, and other indicators of thermal activity. Various methods of identifying thermals at a distance have been proposed. Light scatter from humid air can be distinguished from dry air. Rising hot air will normally be more humid than the surrounding air. A multispectral camera may thus be able to detect thermals, even without the presence of cumulus clouds. However, this method remains to be explored.

By operating multiple UAVs (or other aircraft) in a given area over some time, the meteorological conditions can be sampled regularly. This will allow progressively more accurate forecasts to be made. The longer one has operated in an area, the more experience data can be gathered. Systems will thus “learn” as they go, and become more and more efficient.

2.2.3 Development Strategy

Until the regulatory issues of flying UAVs in controlled airspace are resolved, thermal soaring will need to be piloted. Possible exceptions are to fly unmanned aircraft on thermals inside military Restricted Areas, or to test concepts with small sailplanes at low altitude under visual RC control. Extremely low flying is not necessary, as thermals are mostly too narrow and disorganized below a couple of hundred meters. Manned sailplanes may thus be useful for initial development of methodology and algorithms. An autopilot will suggest actions to the pilot in control of the aircraft.

To explore the full potential of thermal soaring within clouds and other high-risk situations, unmanned platforms are required. The same type of platform will be suitable for both unmanned thermal and slope soaring development. Altitude will in most cases be less than 5 km, so a small, 5 m wing span aircraft is suitable.

Automatic thermal location is an important capability for unmanned thermal soaring, although not critical. An autopilot algorithm for thermal identification and climb-rate optimization (thermal centering) using a variometer is essential.

2.3 Soaring in atmospheric Waves

There are two main types of atmospheric waves that are used by sailplanes: mountain lee waves and convective waves, also called thermal waves. Both types are standing waves, i.e. air flows through a stationary wave pattern. When air passes the wave crest, water vapour may condense to form very characteristic lenticular clouds (Figure 2.3). In the wave troughs there will often be clear air, so called föhn gaps.

Stable air blowing across a mountain range is a prerequisite for mountain waves to develop. A stable layer (an inversion) will prevent a rising air mass from continuing to rise. Leeward of the mountain, the stability will cause the air mass to “bounce” up and down a number of times in a wave pattern. The wave pattern may extend to great altitudes (so-called vertically

propagating waves), or continue for long distances horizontally (trapped waves). Such trapped waves are often visible on satellite images, stretching for several hundred kilometres downwind of the mountain or island.

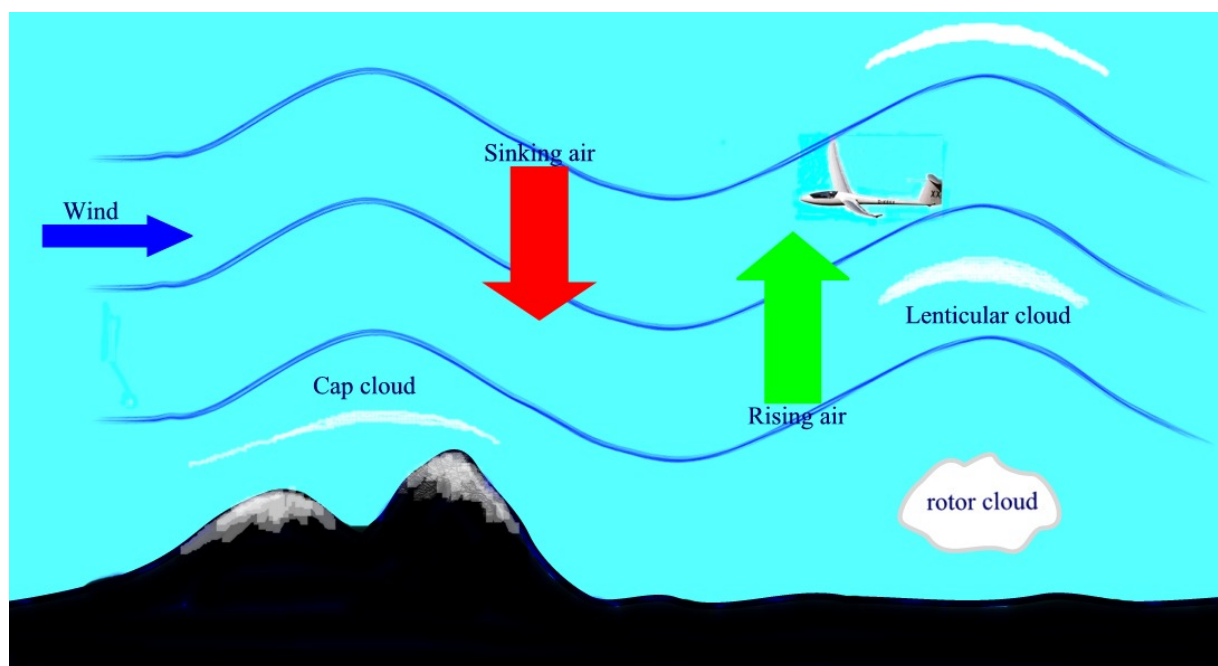


Figure 2.3 Mountain lee waves.

2.3.1 Manned aircraft

Extreme altitude, range and endurance can be realized using waves. Altitude potential is probably more than 30 km (depending on aircraft characteristics and geographical location) although the standing record is about 15 km (21). Wave soaring is often possible at sea (e.g. in the lee waves from an island), but this is not practiced.

Waves are often called “the elevator to the sky” because an aircraft can be lifted vertically to great height without moving relative to the ground (when the velocity of the aircraft relative to the air equals wind velocity relative to the ground). The pilot will seek the strongest area of lift by “easing” forward or backward within a wave period, or by moving upwind or downwind one period to the next wave lift area. Long transverse flights are possible (90 degrees to the wind direction) if waves are caused by long mountain ranges or cloud streets. Lee-wave patterns may be complex when they are caused by irregular terrain. However, they are stationary as long as the wind pattern prevails, and they usually allow long endurance flights. It is not uncommon for wave events to last for several days. Lenticular clouds are good indicators of wave crest position.

Even more important than to find lift and avoid sinking air, is to avoid “rotors”, which are turbulent eddies or vortices often found in the lower part of the wave system. They can be revealed by so-called “rotor clouds” that look like cotton balls or long “rolls of cotton”. Rotors have caused crashes, and are particularly dangerous for slow and light aircraft. Low-flying

aircraft may fall victim to rotor turbulence if such dangers cannot be predicted or observed and avoided.

Most pilots outside the sailplane-community are not very familiar with waves. Simple, “common sense” flight planning without wave knowledge might have disastrous consequences because rotors often occur exactly where many pilots would choose to fly – in the middle of a valley, across which a strong wind may be blowing. Knowledge about waves and rotors will tell a pilot to fly closer to a mountain/valley side than otherwise. This will increase safety, not reduce it, as “common sense” would have it. Waves are a good example of how meteorology may be exploited to our benefit, or “ignored to our peril”(11).

In Norway, the best wave flying conditions occur during the winter season, on westerly winds, and leeward of the mountains along the entire country. The most well known conditions are in the Jotunheimen area, where the Scandinavian altitude record for sailplanes of approximately 10 500 meters has been set. The world altitude record for sailplanes is about 15 000 meters (49 000ft set during the PERLAN project). Lenticularis clouds have been observed above Oslo with estimated altitude twice as high. “Mother of pearl clouds” associated with very high-reaching waves are a characteristic and beautiful phenomenon. The New Zealand/American PERLAN project is named after these clouds, and is aiming to use such high altitude waves to set a new altitude record of 30 km (100 000 ft) with a manned sailplane with a pressure cabin. The European OSTIV Mountain Wave Project (17) aims to characterize wave conditions on a large scale. There are thus several interesting opportunities for cooperation if unmanned wave soaring should be explored.

The “Sierra Wave Project” (11) was the first research and experimentation project to study waves using instrumented sailplanes. During a subsequent project that focused on high level winds and related waves, the “Jet Stream Project”, an instrumented sailplane (a Pratt-Read) was ripped apart in mid air in 1955, demonstrating the enormous brutality of rotors, which are frequent features of wave phenomena. It was estimated that the sailplane had experienced more than 16 G before breaking up into three parts.

The example above goes to show that mountain lee-waves should be respected by all aviators, and that understanding them is crucial to flight safety.

2.3.2 Unmanned aircraft

Manned wave soaring is usually cut short due to pilot discomfort in the extreme cold at high altitude, oxygen supply restriction, fatigue after many hours of flight, lower level cloud build-up or dwindling daylight. To a UAV, these factors are not important.

The ability to reach high altitudes means that a UAV system should be designed to operate under very low temperatures, typically $-56\text{ }^{\circ}\text{C}$, as well as low pressure. This has implications for power systems, structure and avionics. Under favourable wind conditions, endurance will be limited only by power supply to sensors, avionics and communications systems onboard.



Figure 2.4 Waves above Vågå, near the Jotunheimen-mountains in Norway. The wind is blowing from right to left in this photograph. Lenticularis (lens shaped clouds) are characteristic features of mountain lee waves, and can be used to locate wave lift. Lift would be on the right side of the clouds in this case. “Veils” downwind of the lenticularis clouds are not very common.

2.3.3 Development strategy

Basic wave soaring capability can be realized without advanced wave forecasts. A general weather situation combined with qualitative knowledge is enough to (roughly) predict the occurrence and location of wave activity. Waves are remarkably predictable, given a particular set of conditions. Sailplane pilots are often good at recognizing favorable conditions in familiar areas.

Lenticularis cloud recognition and improved forecasts will be a great advantage, and will aid the UAV in narrowing down the search for lift. Autopilot lift-search algorithms using variometer input are critical for autonomous unmanned wave soaring. Automatic lenticularis cloud recognition and atmospheric modeling is important, but not critical.

Much of the developmental experimentation can be done using conventional manned sailplanes. However, the full potential of wave soaring will not be uncovered without unmanned platforms. Multi-day missions, and flight in extreme conditions will require suitable unmanned aircraft.

To explore modeling possibilities, high-resolution computer models should be tested on historical flight log data in a chosen test case. Adjustments can be made to model parameters if needed. When satisfied with the models fidelity to reality in the historical case, the model may be applied to other historical meteorological data to explore the frequency of wave occurrences in both the test area and larger regions if funding allows. This would reveal whether usable waves occur frequently enough, and are so predictable that it is worth pursuing the unmanned wave soaring concept further.

The next step may be to test model predictions by flying high performance (motorised) manned sailplanes equipped with suitable sensors, data-loggers and full IFR (Instrument Flight Rules) instrumentation, in the areas of predicted lift. The model may thus be developed further (if necessary) based on flight experience.

If the model predictions prove satisfactory, the main focus may be shifted towards implementing autopilot algorithms. An “autopilot” may generate guidance to the human pilot for locating the best lift based on model output, keeping the aircraft in the strongest lift, and for optimizing the glide path and speed on cruise. The pilot will be in full control of the aircraft. The autopilot may initially be located in a ground facility, sending simple guidance data to the pilot by voice or data communications, or it may be implemented in a portable PC and used by an operator in the rear seat of a two-seater sailplane. By the end of a first test program, the utility of unmanned wave soaring, and any development difficulties, should begin to be apparent.

For piloted aircraft that are equipped with transponders, access to controlled airspace is not a problem. Extensive test flight programs will be routine, and just as safe as any other sailplane activity.

2.4 Dynamic soaring

Wind shears, e.g. near the surface, around the edges of the jet stream and temperature inversions, can be used by aircraft to gain energy. The most proficient user of the technique known as “dynamic soaring” (DS) is the Albatross. It flies long distances (several thousand km) at sea at less than 50 m above the surface. The largest Albatross (the Royal Albatross) has a wingspan of about 3,5 m, an aspect ratio of 20 and weighs up to 10 kg. This means that it has a relatively high wing loading for a bird (about 160 g/dm²). The best L/D is 20, which is impressive given the low Reynolds numbers it operates within. The closest UAV-analogy in terms of size and weight would be the SeaScan (ScanEagle) (25) or the Aerosonde (24). The transatlantic and transpacific flights made by the Aerosonde are made at a low altitude, where dynamic soaring could be ventured, had the technology been developed. No UAV system has yet employed DS-techniques.

The dynamic soaring technique has been experimented with in manned high performance sailplanes, and is routinely performed with model airplanes.

There are several dynamic soaring techniques in addition to the one using horizontal wind shears. Examples are “vertical gust dynamic soaring” (in which an aircraft may actually gain energy from a downwind gust), “side gust dynamic soaring” and “thermal vortex dynamic soaring”. References found in this report explain the concepts further.

Unmanned dynamic soaring could be ventured in far more “risky” conditions than with manned aircraft. The development should be done with small, low cost aircraft. These aircraft must be able to withstand very high acceleration loads, due to the sharp turns and high velocities in dynamic soaring.

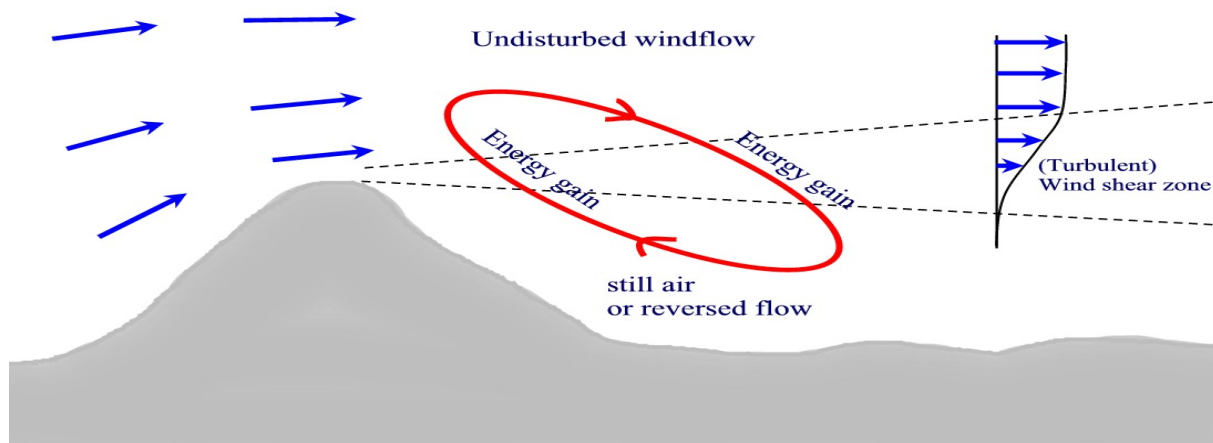


Figure 2.5 Dynamic soaring. For every pass that is made by an aircraft through the pattern shown, energy is gained. Unpowered model airplanes have reached velocities of several hundred kilometres per hour by circling in a wind-shear zone.

3 FLIGHT OPTIMISATION

To conserve energy it is essential to fly the path that will probably give the most up-wind and the least down-wind. The optimal track will usually deviate from a straight line, and will depend on slope soaring conditions, thermal conditions, wave conditions etc. The predicted horizontal wind vector component must also be taken into account. In case of a strong headwind component it may be appropriate to fly low to minimise headwind velocity. In a tailwind, it may be appropriate to fly high and slowly – so-called “ballooning” - to minimise fuel consumption. Optimisation may take place both before and during a mission.

3.1 Pre-flight planning

Even though exploiting rising air, and avoiding headwinds etc is possible, it may not always be worth a “detour” from a straight line. Human operators or autonomous software (most likely a

combination) must decide which flight strategy to adopt within mission constraints. A maximum allowed time-to-target and largest allowed deviation from a given path or location (i.e. a corridor) should be specified. Software will then be able to construct an overall mission-plan that adapts well to given meteorological conditions while satisfying the requirements.

The overall mission plan will maximize the probability of lift and safe flight, avoid headwinds and use tailwinds as far as possible within the mission constraints. It will also provide the constraints for a short-term plan, which is updated almost continuously (in-flight) based on new input. The capability to use meteorology in an overall planning system is the first step, or the core, in the soaring UAV concept (“implementation level 1-2”). The short-term flight optimisation is possibly where the greatest performance gains can be made, using detailed forecasts, sensor input and soaring control algorithms. This is also where the more challenging development work lies (“implementation levels 2-4”).

Flight planning software should select a flight path, altitude and airspeed that allows the mission to be accomplished with increased energy efficiency compared with existing systems. The potential in such a system can be explored in simulations, but only actual flight experience will reveal its “real-world” value.

Fully computerized flight path optimisation will be a vital capability in order to achieve autonomous operation, and to relieve workload when planning automatic operations (which is what is done today).

3.2 In-flight optimisation

The overall plan may build upon the larger forecast weather picture (resolution will depend on computational resources), whereas the short-term plan may use more detailed models (that are run during the mission) as well as sensor input. An example of a short-term plan may be to deviate 500 m from the nominal flight path (corridor centreline specified in the overall plan) to exploit wave lift. The aircraft will then rely on its own sensors to locate the best lift. It will continuously check that it will be able to stay within the overall plan with a given safety margin.

Sensor input may be from both external sources (other UAVs, ground based sensors etc.) and onboard sensors. Both the overall and the short-term plan may be changed during flight.



Figure 3.1 Flight-path optimisation performed in the “Silent Wings” flight simulator developed by Simula Research Laboratory AS in Oslo, Norway. The blue (wiggly) line represents the path that maximises the probability of lift given the current weather forecast. At some points along the path, thermals or strong slope lift is exploited to gain extra altitude (shown as “knots” on the blue line).

3.3 Airspeed optimisation

Having selected a flight path, there is always an optimal speed-to-fly (“optimal” depends on the mission objective: to stay airborne the longest possible time, or to get from A to B as fast as possible). In rising air, speed should be reduced to remain longer in the rising air. And in descending air, speed should be increased to get quickly through, with minimum altitude loss. Consequently, when flying through areas of variable rising and falling air, the (unpowered) aircraft will fly a wavy pattern, sometimes called “dolphin flight”. The optimum speed-to-fly has been subject to comprehensive research. Paul McCready and others (see Reichmann) have developed several theories. A suitable speed-to-fly algorithm should be rather straightforward to implement in a UAV autopilot. It should be noted that such an algorithm is equally suitable for powered flight.

4 FORECASTING

During World War II, the altitude and speed performance of aircraft improved vastly, and this led to a number of important new discoveries. Among these discoveries were mountain lee waves, jet stream winds and transonic effects. During the war, the number of meteorologists grew considerably worldwide. This coincided with important developments in the field of meteorology in general – developments in part led by Norwegian scientists.

Since the war, ties have been close between soaring pilots and meteorologists. As a result, forecasting for soaring has been explored in depth. Sailplane pilots enjoy routine standardized forecasts, focusing in detail mainly on thermals.

With the developments in computer modeling, new possibilities for (soaring) forecasts are now emerging. High-speed data communications brings new possibilities in dissemination of forecasts to users as well. Fine-scale (e.g. 1 km resolution) model simulations are not used routinely in aviation today. They have however proved useful in investigations into possible causes of accidents (7).

Forecasting for soaring UAVs may be mainly a question of organizing and using already existing capabilities in a new way. Models should probably be run both centralized and decentralized, depending on computing requirements, time and cost aspects. Meteorology and geographical information systems for UAVs could be integrated with NATO Rapid Environment Assessment (REA) and other Meteorology and Oceanography (METOC) services. Military aviation meteorology services in Norway will possibly be upgraded within the next few years. UAV meteorology needs should be viewed in this larger context.

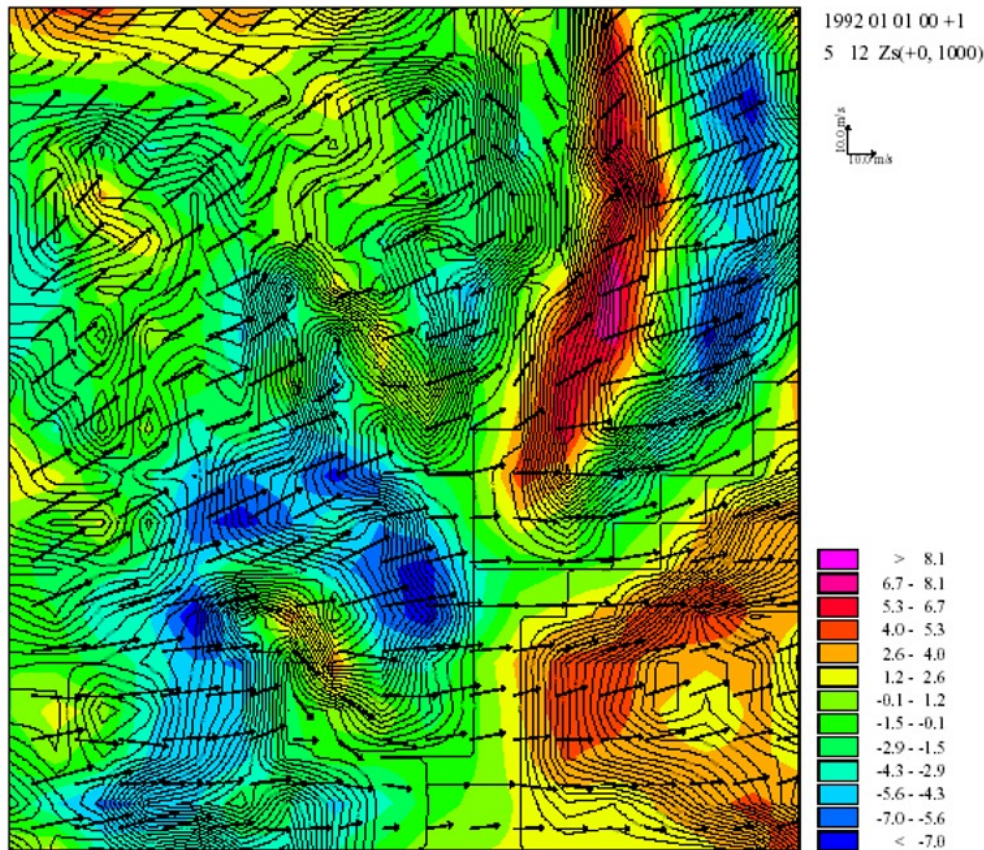


Figure 4.1 Local wind conditions in Fjerlandsfjorden at 340 m above sea level during a storm in January 1992, as simulated by the MC2 model (1 km resolution). The wind direction is from the left. The arrows give the wind direction and horizontal component magnitude. The colour shading gives the vertical wind components. Vertical velocities approach +/-8 m/s. The model also predicts possibility of turbulence. (Courtesy of DNMI)(6)

4.1 Forecasting slope wind

The synoptic wind forecast is probably sufficient to predict roughly which ridges may be soared and which ones should be avoided e.g. due to possible down-draught and turbulence. Advanced modeling is not critical in all cases, but will provide for more efficient and safe flight in complex terrain. The general wind direction at high altitude will not normally be the same as for local low level wind around valley bends etc.

Stronger lift is associated with higher chance of turbulence and wind reversals, which can be very dangerous when flying close to the ground. More ambitious slope soaring, which aims to use even the most dangerous or the weakest lift, will require fine scale modeling. The computational “cost” of predicting fine scale wind and turbulence for individual ridges, and the possible benefit of doing so, should be investigated.

Existing models, such as the MC2/SIMRA (SIMRA is based on SAFRA) model system developed by SINTEF (31) and DNMI (3), appear to be able to predict low-level winds quite well (Figure 4.1). The resolution is a few hundred meters. However, sensor verification has not been available to validate model predictions properly.

4.2 Forecasting thermals

Forecasting all kinds of thermal activity accurately is very difficult (5). Fortunately, qualitative knowledge and experience goes a long way. Systematizing knowledge and flying strategies and developing autopilot algorithms (that use onboard sensors) will be a good start towards an unmanned thermal soaring capability. Given a probability assessment of thermal conditions, a search pattern can be executed, just like sailplane pilots do today.

Use of thermals by sailplane, paraglider and hang glider pilots is well established. Their close communication with meteorologists has contributed to the development of methodology for forecasting thermal convection activity. The Swedish SMHI (26) thermal forecast is much used by Scandinavian soaring pilots. One thermal forecast example is shown in Figure 4.2 (soaring from Hamar to Sundsvall would be easy on such a day).

Up-to-date soundings from aircraft or balloons are helpful in predicting thermal activity (information on vertical profile of temperature, moisture and wind is important). One problem is that the release of thermal bubbles from the surface is to a great extent stochastic, depending on turbulent ground-level wind, vehicles, and other activity.

Insolation depends on latitude, cloud cover, season and time of day. Surface properties like albedo and heat capacity are very important for the transfer of radiative energy. A detailed and up-to-date database of the surface is therefore necessary, as well as information about the actual surface conditions at the time. If no other sources of detailed surface and insolation conditions are available, a UAV flying far from its ground control station must provide such information to the forecasting computer.

Given that sufficient information is available, it is possible to forecast the following:

1. Area where convection will probably occur
2. When it will begin
3. How long it will last
4. How high it will reach (cloud base and top)
5. The strength of the thermals (rise velocity)
6. If precipitation or thunderstorms will develop
7. The direction and velocity of lateral drift due to wind

Simple forecasting tools can be implemented on personal computers today, and thus also onboard small aircraft. The computing resource requirements, time-aspect and need for sensor input of thermal forecasting should be explored further.

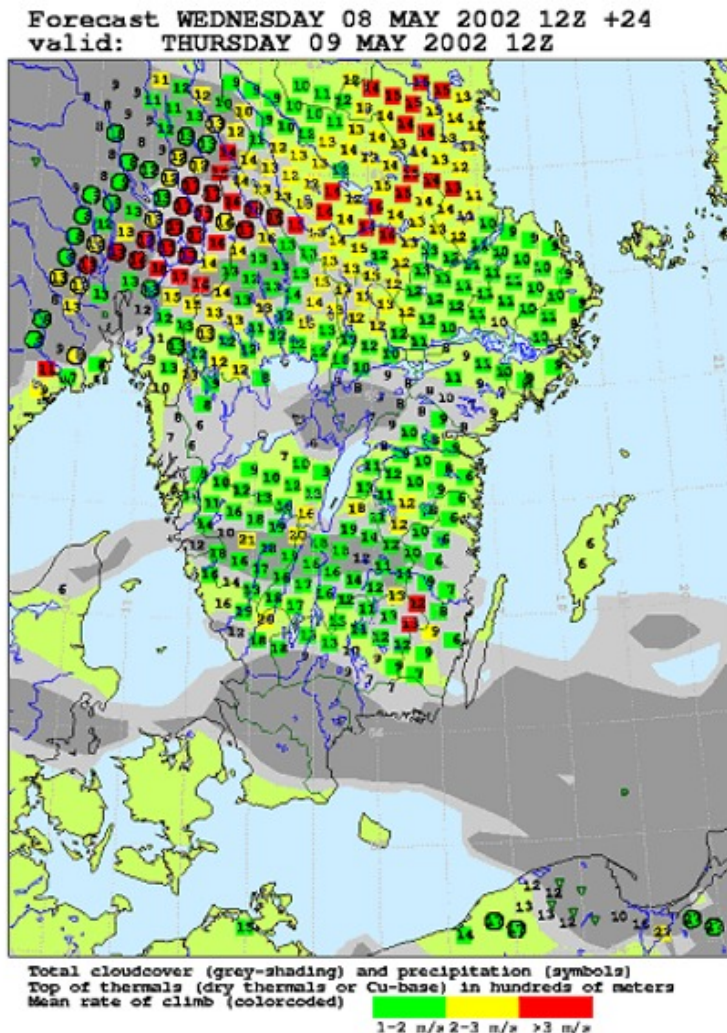


Figure 4.2 Swedish SMHI thermal forecast for southern Sweden and parts of Norway. The forecast is available on the Internet (26).

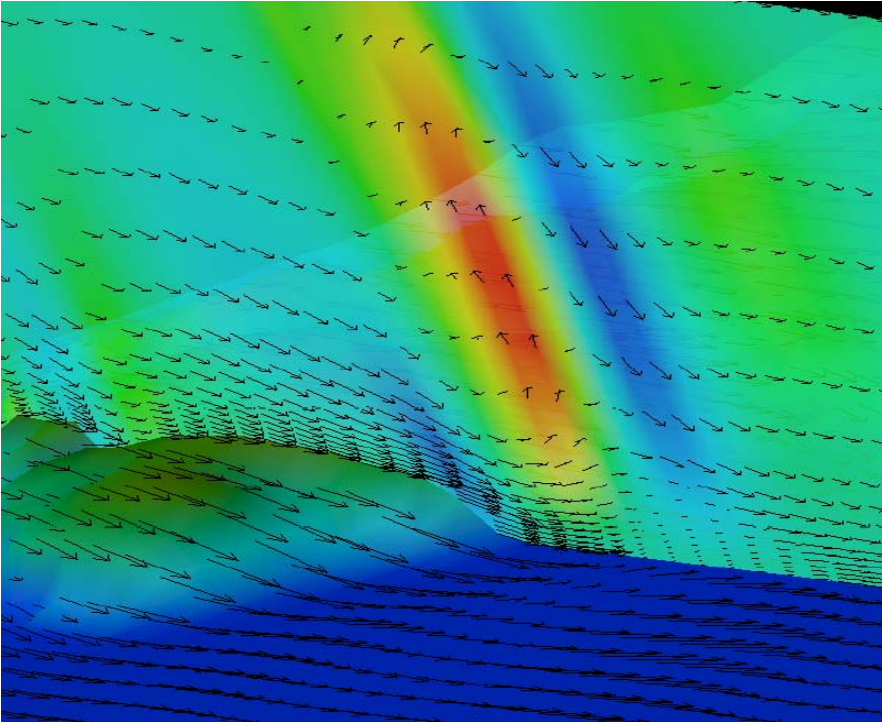


Figure 4.3 Cross-section of a wave event output from SIMRA, a fine-scale three-dimensional flow model. The terrain feature shown is about 450 m high. The vertical distance between the grid-points varies from 30 m near the terrain, to 300 m higher up. The horizontal grid resolution is 1 km. The model continues to 20 km altitude but is visualised here only up to about 2200 m. Red indicates strong updraught of about 8 m/s, and blue indicates a downdraught of about 5 m/s. (Courtesy of DNMI)

4.3 Forecasting mountain waves

Prediction of mountain waves is very complicated (2)(4)(5)(10) and is the subject of advanced atmospheric research. However, existing models are able to predict wave activity reasonably well. The Naval Research Laboratories (NRL) Mountain Wave Forecast Model (MWFM 2) is an example (18). This model has been used to study the frequency of occurrence of mountain lee waves in many parts of the world (Figure 4.4). The MWFM was used to support the NASA MACWAVE project (20), which studied mountain lee waves in northern Norway and Sweden in 2002-2003.

Mountain waves are not included in routine aviation meteorology services today - neither civilian nor military. The possibility of including wave forecasts in routine services should be explored further.

In a co-operation between the Norwegian Meteorological Institute (Norwegian acronym DNMI) and the Norwegian Defence Research Establishment, steps have been taken to test an advanced fine-scale model system (MC2/SIMRA) on a chosen prototype area on a given day in the past, which is known to have been a good wave-soaring day. Model output data was ordered from the DNMI for the Vågå area, near the Jotunheimen mountains. Vågå was chosen

because it is a very popular wave soaring site, known for the “Extreme Altitude Challenge” (also known as the “Vågå Wave Camp”(27)). A large amount of GPS flight log data is available, and the model output can be compared to the actual flying conditions experienced on any given day. Recent developments within the DNMI have rendered the completion of this work uncertain.

In the state-of-the-art model used by DNMI in this study, detailed topographic data are combined with the fine-scale atmospheric flow models MC2 and SIMRA to simulate, among other parameters, wind velocity and direction profile (and thus, predict areas of lift). Input is from the Global HIRLAM (10 km resolution) model, which is routinely used to generate weather forecasts.

An example of the type of 3D flow field output (visualized for analysis) that is possible is given in Figure 4.3. It shows a pronounced wave feature in the lee of a mountain, and is a good example of how a model system, if sufficiently true to real conditions, can localize areas of lift and downdraught. Shifting the flight path a few kilometres (in the example shown) results in a great difference in total energy change per second for an aircraft. It is currently unknown if the model simulations may be run in semi real time in the field, or if the computations must be performed in a centralized location.

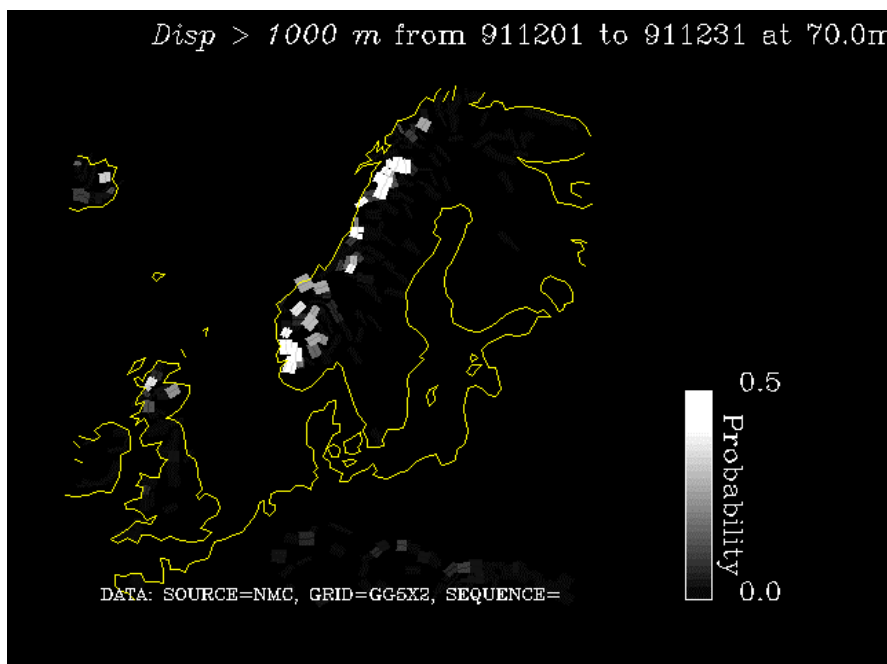


Figure 4.4 Mountain wave climatology for northern Europe developed by the United States Naval Research Laboratories. The model MWFM2.0 has been used to simulate wave events that reach about 20 km altitude for a number of (large scale) mountain ridges based on historical weather data input. The number of wave occurrences was counted for the entire month of December in 1991, and divided by the number of days. The lighter the colour of the rectangles, the higher the probability of waves on any given day. Many locations in Norway had a 50 % chance of waves every day in this month according to the model.

5 AIRFRAMES

All aircraft operations benefit - in terms of efficiency and safety - from in-depth knowledge of the atmosphere and from good weather forecasts. But not all aircraft types are equally suitable for exploiting rising air without engine assistance. The importance of the safety gains is also dependent on platform characteristics. Designs with little power surplus and very light structures with low G-tolerance are most vulnerable to dangerous conditions like icing and turbulence.

This chapter discusses characteristics of existing and potential future UAVs in the context of soaring. Design concepts are presented for a new type of platform that will be well suited for experimentation with unmanned soaring and that may fill a “very long endurance niche” in the UAV market.

The actual gains of applying soaring strategies to different aircraft types should be explored further, and weighed against the costs. A simulation environment will be very helpful in determining whether soaring is worth the extra system complexity.

5.1 Existing airframes

5.1.1 Existing UAV systems

The benefits of applying soaring methods to existing UAV systems depends on the aerodynamic efficiency of the airframes. The ability to use rising air to gain altitude, and the ability to convert gained altitude to flown distance varies. Most existing UAVs (or other aircraft) will have to fly with the aid of engine power even when they are “soaring”, e.g. in thermal or wave lift. The reason is that the sinking speed of the aircraft is greater than the vertical velocity of the air mass. For example, a typical tactical UAV (a TUAV) may glide with a sink speed of up to 10 m/s when the engine is cut. This means that it is not able to use atmospheric lift to rise without engine assistance.

Although many existing UAVs are more or less motorized gliders, they cannot become “true soarers”. Payload weight and airspeed have dominated the design process over aerodynamic efficiency. The airframes seem to be a cost reduction area, leaving great room for improvement. Experimenting with existing platforms should, even so, provide interesting and useful results. Extending e.g. TUAV endurance by an hour or two (about a 25 % increase) seems quite possible in many cases just by flying “smarter”. This would enhance their usefulness considerably.

The only way to experiment with advanced unmanned soaring techniques, however, is through very efficient unmanned airframes of a sailplane type.

5.1.2 Scale sailplane models

The need for a low cost airframe for development of soaring at low altitude was discussed earlier. Large-scale (1:2,5) sailplane models are readily available on the civilian market. As tempting as pure COTS-choices are from a cost perspective, these airframes have some traits that make them less than ideal for the job.

Concept development requires the capability to carry some sort of payload and engine besides the usual RC-equipment. Autopilot, mission computer, data logger, communications equipment, sensors, batteries, engine, fuel etc. will add several kilos to the total weight. Model sailplanes that could in principal carry such loads, are in the 5-8 m wingspan range. The aspect ratio is usually high (around 20-30, to maintain scale appearance). The wing area, and thus load carrying capacity, is therefore too small to carry the desired weight without having to fly at a very high angle of attack, which causes high drag (the glide ratio becomes very poor). A typical wing-area for such a glider is 1 m², whereas about 1,7 m² would probably be more appropriate.



Figure 5.1 Examples of large-scale model sailplanes. Top picture in the foreground: an ASW 15b in scale 1:1,25, with a wingspan of 6m and a total weight of 19 kg. Bottom picture: a 1:2,5 scale SHK of 6,8m wingspan and 25 kg total weight. The towplane (a Wilga, 1:2,5 scale also) is in the background in the top picture.

Large model aircraft are usually scale models. This means that they are designed to look like the manned aircraft. This always causes a performance penalty compared to other airframes that are designed purely for their intended use. Scale models have lower aerodynamic efficiencies than the full size versions and purpose-built airframes (lift-to-drag ratios are often around 10:1 for the model compared to 50:1 for the full size aircraft). To compensate for this lower efficiency, scale models are designed for very low wing loading. This is achieved by cutting weight wherever possible, resulting in airframes that usually do not have the structural strength or stiffness required for flight in very strong wind and turbulence.

The airfoil camber (a measure of the curvature) often used for such scale gliders is 3 % or more. 3-3,5 % camber is well suited for thermal soaring, but not for the ability to penetrate (to fly upwind without engine propulsion) when the wind-speed exceeds about 10 m/s. A wing camber of 1-1,5 % is within an acceptable range where both needs are taken care of. It gives the ability to fly with good performance in no or little wind, as well as when the wind is stronger. Commercially available sailplane models will have problems under these differing conditions.

All control surfaces should be hinged to the wing-panels in order to withstand the effects of varying temperatures on different materials (different expansion). On model sailplanes, tape or simple plastic hinges are commonly used. This is not suitable for a UAV that must operate under all weather conditions, with possibly great stresses.

In conclusion – commercially available scale model sailplanes are not well suited for unmanned soaring concept development. The ideal platform would be stronger, have a larger wing surface area, use different airfoils and would be designed for all-weather operation.

5.2 The soaring UAV concept

A “true” Soaring UAV (an SUAV) is an “extreme design”. It will be far more carefully designed with respect to aerodynamic efficiency than current UAVs are. A definition of a Soaring UAV must build on both the airframe design and the way it may be operated:

A soaring UAV is an unmanned aerial vehicle with aerodynamic performance comparable to the best sailplanes of comparable size, which can effectively exploit upwinds to gain altitude without engine power assistance.

The design of an SUAV will give a higher priority to endurance and range than to payload capability and velocity. The airframe will be designed for cruising at modest to low speed, and will probably share many design features with high performance sailplanes. A practical and reliable SUAV will need to have engine power available to traverse areas of limited atmospheric lift, sinking air or strong headwinds. In contrast to motorized sailplanes, engine power may be required over long periods of time to maintain altitude and airspeed in adverse conditions, and possibly to generate power for onboard systems (e.g. sensors). The power surplus will be small to maintain low propulsion system (and thus overall) weight. This means

that an SUAV will not be quick to deploy to distant mission areas compared to some other design types. Cruise airspeed will typically be around 100 km/h, depending on size and other factors.

SUAVs may be well suited for missions such as loitering communications relay and surveillance (12). In these mission types, a low percentage of the total mission time will be spent in transit, and platforms will relieve one another in succession. The low speed of the SUAV will only be a drawback when a single platform is required to deploy quickly to a distant mission area. In many cases, the capability to loiter for a long time, with a low radar, thermal and acoustic signature, may make up for the relatively long time it takes to deploy a platform. Longer endurance also means that fewer platforms will be needed to perform continuous coverage of a given area.

A way to increase long-range availability (compensate for low speed) is to distribute a “swarm” or network of SUAV platforms over an area of interest (12). Instead of “worrying” about getting the payloads to the desired location quickly enough, it may simply be a question of redistributing the network nodes according to changing needs. Low cost and very long endurance are prerequisites for such multi-platform concepts to be feasible.

Icing is a problem that will affect SUAVs just as much as other aircraft designs. Perhaps more, since the power surplus will be small, and it may not be possible to accommodate an enduring anti- or de-icing system. Highly efficient low Reynolds number laminar flow airfoils are very sensitive to ice and insect buildup. An effort must be made in forecasting and flight planning to avoid icing conditions. There will be a fine line between exploiting lift inside clouds and entering an icing zone.

Soaring UAVs will have to be fairly robust to operate safely in all kinds of weather. A true soaring UAV should be able to exploit any conditions that manned sailplanes can exploit - and more. The ability to operate in extreme weather, and take advantage of what is traditionally characterized as “bad flying weather” is an important goal.

5.3 Small or medium sized Soaring UAVs

It has been established that small, low cost airframes that would be suitable for advanced soaring UAV concept development do not exist. Any airframe development with such use in mind should also aim for flexibility in future applications and technology upgrades. The design will represent a balance between cost, practicality and capability.

The objective for a demonstrator design would be an experimentation capability with high aerodynamic performance and upgrade potential. The initial demonstrator design must be adequate to develop unmanned soaring concepts at the lowest possible cost.

The following sections contain design ideas for a low-cost UAV that is suitable for “high risk” soaring concept development. Further preliminary details of a proposed design are included in

Appendix A. The cost goal for this particular design is NOK 150 000 or less for one platform, including actuators, engine, RC-equipment and autopilot (the costs are specified in Appendix A). This excludes all ground equipment and necessary man-hours. The latter will undoubtedly represent the greatest portion of the total cost.

A summary of reasonable requirements for a demonstrator SUAV is included in Appendix A. A goal of three days endurance is chosen simply so that the aircraft will have a longer endurance than any other UAV currently available (the endurance limit is typically around 48 hours for a medium size UAV). The goal is to use the engine during at most one fourth of the total endurance time of 72 hours, giving a required engine time of 18 hours. This is comparable to a SeaScan or Aerosonde UAV, and is considered a realistic target. The endurance uncertainty will lie mainly in achieving the remaining 54 hours, which will depend on the atmospheric conditions.

A design that satisfies the requirements may have many design features in common with a full-size sailplane, with a swallow-shaped, high aspect ratio wing geometry, and a slender streamlined fuselage (Figure 5.2). To avoid very low Reynolds numbers, and to allow for high G-tolerance, the aspect ratio should be limited to about 15, in contrast to full-size sailplanes, which often have much higher aspect ratios.

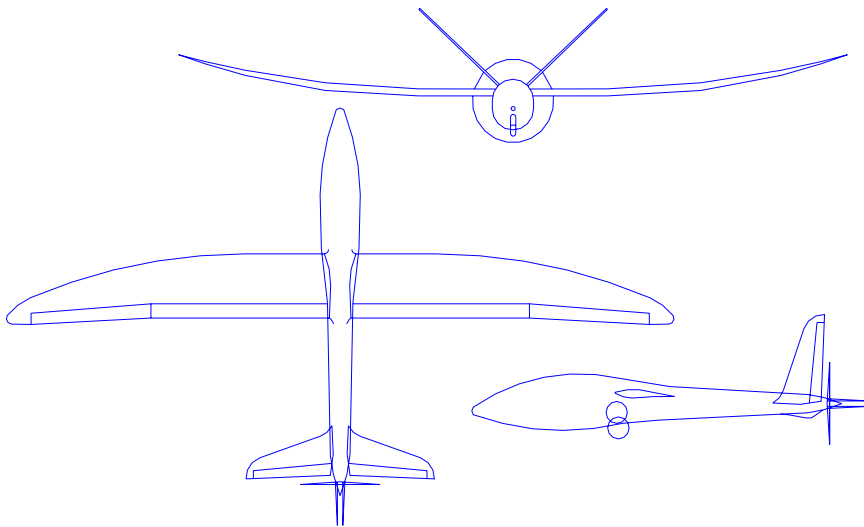


Figure 5.2 Proposed layout for a small or medium sized soaring UAV airframe. The wingspan may be between 5 m and 10 m, and the total weight between 25 kg and 50 kg.

A prerequisite for achieving low cost in such a UAV will be to keep the payload weight and overall complexity down. A modest payload weight and power requirement allows the use of low-cost “model airplane” powerplants, low airspeed (which is more efficient) and lighter, less expensive structures. A proposed general layout is illustrated in Figure 5.2. The engine may be mounted in the rear of the fuselage between the V-tail surfaces or in the central fuselage area

and connected to the rear pusher-propeller via a drive shaft. The pusher-propeller should fold backwards when not operating to reduce drag.

Since a demonstrator would be aimed at being realised within the near future, and within a low budget, power supply would have to come from a combination of internal combustion engine and batteries. Most of the total time it is airborne, a demonstrator SUAV should probably run on battery power. The total endurance of 72 hours could possibly be achieved by carrying about 10 kg of fuel (for a 5 m wingspan version), but this solution would not harmonise with the main point of such a demonstrator, namely to develop unpowered unmanned soaring technology and concepts of operations.

Increasing the size from about 5 m to between 8 m and 10 m wingspan would improve performance potential substantially in terms of glide ratio and altitude (glide ratio would probably increase from 20 to 30). Such a medium sized aircraft would also allow advanced unmanned wave soaring at high altitude (20 km+) to be developed to its full potential. An SUAV roughly half the size of a full size manned sailplane may have the potential for one-week endurance, and a payload capability that would compete with current tactical UAVs (TUAVs).

5.4 Large Soaring UAVs

Unmanned versions of full-size sailplanes are in development (e.g. the Stemme S15-8 (30)). Some “one-off” examples exist already. A full-size sailplane will be able to compete with current MALE UAVs and large TUAVs in terms of payload weight and size.

The prospects of developing a soaring UAV from a commercially available manned sailplane design has been discussed with the German manufacturer Lange Flugzeugbau (22), which employs a number of Norwegian engineers. The Antares motorized sailplane developed recently (Figure 5.3) is the first electrically powered manned aircraft ever to enter series production. It features 80 kg of SAFT (manufacturer name) (2) Li-Ion batteries storing 12 kWh of energy, permitting the aircraft to climb over 3000 meters during each flight. After the ascent, the electric motor and slow-rotating propeller are automatically retracted into the fuselage. With the propeller retracted, the aircraft has a maximum glide ratio close to 60:1, in part thanks to an aspect ratio of 32 and an ultra-thin airfoil. A glide in still air from 3000 m altitude gives the Antares a range of 180 km. The descent would take about one and a half hours, if no other sources of lift were encountered.

The aerodynamic shape of Antares is the result of extensive use of computer models and wind tunnels. The moulds have been made using large computer-controlled milling machines. This ensures accurate reproduction of the design shape. The never-exceed-velocity (Vne) of the Antares is 290 km/h, and a flutter-proof design has been achieved using advanced carbon fiber construction techniques. During static load testing the Antares wing collapsed at 17 g.

The 20 meter wingspan Antares may be well suited for conversion to a long range, long endurance UAV, although the folding motor/propeller configuration may not be ideal (the motor should only be used in short periods and then stowed because of the increased drag when it is deployed). The spacious cockpit and fuselage may be used to house the power generation (fuel cell or piston engine & generator) and the mission payload systems. The Antares nose is designed to house a gimbaled high definition TV camera by replacing the standard carbon nose dome with a glass dome. The cockpit could accommodate a 500mm diameter gimbaled dish antenna, to enable real-time high data-rate satellite communications.



Figure 5.3 The Lange Flugzeugbau Antares prototype in flight with the engine deployed (Photo courtesy of Lange Flugzeugbau, Germany).

6 SIMULATION

A simulation environment will be an important element in both the development and operation of the soaring UAV concept, as for most other complex systems. Computer simulations based on precise representation of terrain, weather conditions, UAV aerodynamics etc. can be used for several important tasks, including:

- ❑ Concept development and prototyping
- ❑ Airspace management planning
- ❑ Mission planning
- ❑ Flight path optimisation
- ❑ Piloting, especially in low visibility conditions (or when video is not available)
- ❑ Pilot training

Aerodynamic and atmospheric phenomena cannot yet be simulated in great detail. Practical experimentation will provide vital input and realism to the simulations.



Figure 6.1 Remote piloting in the Silent Wings simulator developed by Simula Research Laboratory AS, Oslo, Norway. The picture on the left was taken from the pilot position in dense fog. The picture on the right shows the simulated view, based on a detailed terrain model and aircraft telemetry data.

The (S)UAV simulation system should include the following elements:

- ❑ A high resolution terrain model and thematic information connected to the terrain (GIS, Geographical Information System)
- ❑ A near real-time weather model including a high resolution wind field
- ❑ Models for soaring in slopes, mountain lee-waves, thermals and more
- ❑ A model of the UAV including its aerodynamic properties
- ❑ UAV operation controls for simulated flights allowing both autopilot and human pilot operations
- ❑ Communication simulations
- ❑ Visualization system for situational awareness
- ❑ Functions for computing optimal tracks under the given physical conditions and mission constraints

Some of these functions are included in existing UAV ground control systems. Some will need improvement or development.

Figure 6.1 is from the Silent Wings flight simulator developed by Simula Research Laboratory AS, in Oslo, Norway. This system satisfies many of the conditions above including high quality terrain, weather, rising air models (thermals, slope wind), aerodynamic models, nearly photo-realistic visualization, as well as full piloting control over the simulated aircraft. Basis for this example is the *Antares* powered sailplane.

7 CONCLUSIONS

The goal of this work has been to present the idea of unmanned soaring, and point out possible ways toward implementation. It is proposed to make use of recent developments in aerodynamics and fine-scale meteorology, as well as to implement more active use of well-established meteorology services and flying know-how.

It is envisioned that unmanned aerial vehicles may adapt to adverse weather more effectively than presently to avoid degraded performance, or even exploit weather phenomena and thereby achieve considerably improved performance levels.

The concept involves adaptations to - or new developments within – the following areas:

- ❑ Airframe technology (the SUAV)
- ❑ Weather forecasting (existing and advanced fine-scale forecasts)
- ❑ Planning and simulation (pre-flight and in-flight route optimisation)
- ❑ Flight control technology (sensors and software for unmanned soaring)

Manned aircraft may be used to develop parts of the unmanned soaring concept. The full concept, e.g. with very low-level slope soaring, may however only be realized with unmanned platforms.

A new type of highly efficient, endurance-optimised unmanned aircraft called a “Soaring UAV” (SUAV) is proposed. Three different design sizes for soaring UAVs have been discussed. These aircraft may be ideal for long-loiter communications relay, surveillance and scientific missions, where long endurance is important.

Four different levels of ambition for implementation of the unmanned soaring concept are proposed:

7.1 Implementation level 1

Implement flight path optimisation that makes use of existing forecasts, sailplane flying know-how and geographical information. Probability of lift, sink, clouds, precipitation, turbulence and other dangers etc. will be roughly estimated. Subtasks may be as follows:

- a) Explore current meteorology services in greater detail. What is possible today without making significant changes?
- b) Establish a simulator environment as a planning/mission management/training aid and to evaluate new concepts.
- c) Establish algorithms for flight planning and optimisation (pre-flight and in-flight) using available information.

7.2 Implementation level 2

Use more detailed forecasts in flight planning and mission management. A higher degree of accuracy in prediction of wind vectors etc. is the goal. New meteorology services for flight operations may be based on models that are used within the science community. Subtasks may be as follows:

- a) Explore the topic of advanced fine-scale meteorology in greater detail. What is the state of the art? What are the computing and time requirements? What input is required?
- b) Establish a soaring climatology for Norway. That is - statistics of wave and thermal occurrence etc. This implies using existing fine scale computer models with historical weather data as input.
- c) Will the added performance be worth the extra system complexity and development effort (based on point a and b)?
- d) Establish cooperation with researchers, pilots and other related projects (domestic and international). How may a soaring UAV meteorology initiative fit in with other activities such as REA (Rapid Environment Assessment)?
- e) Establish flight-planning software that may exploit the new forecasts.

7.3 Implementation level 3

Develop autonomous soaring algorithms that allow in-flight optimisation within boundaries set by an overall flight plan. Sensors and software will give the ability to locate and exploit lift etc. Subtasks may be as follows:

- a) Develop autopilot algorithms for slope, thermal, wave and dynamic soaring. Experimentation with manned and unmanned aircraft will be essential input to theoretical work.
- b) Develop or adapt hardware and software for automatic recognition of clouds and thermals.
- c) Develop a low-cost soaring UAV demonstrator that may be used for high-risk flight experiments.

7.4 Implementation level 4

Develop high-performance airframes for a new type of long-endurance UAV – the SUAV. These aircraft will be capable of utilising a wide range of lift-phenomena for extreme endurance and greater active stealth (low, cool and silent flight) potential. They may be based on commercially available sailplane designs.

A APPENDIX. DEMONSTRATOR DESIGN DETAILS

The following sections contain details of a suggested demonstrator SUAV design. It is meant as a first iteration only. A thorough design process is necessary, and will surely lead to a somewhat different design.

A.1 Demonstrator requirements

The requirements may be as follows:

- Propulsion assisted, with sufficient power to maintain altitude and to climb under its own power with a climb rate of at least 1 m/s in standard atmosphere
- 72 hours full electronics and payload systems endurance
- An engine-on endurance that allows for transit / maintenance of altitude without upwinds (in standard atmosphere) for a period of 18 hours minimum (one quarter of the total endurance requirement)
- The motor must have a self-starter for in-flight re-starting
- Take-off may be by catapult, towing or other method
- A generator must provide power to charge batteries and power all systems when the engine is running
- Maximum runway length for landing is 100 m
- Capability to efficiently utilize atmospheric lift under a wide range of conditions
- Redundant flight termination system with parachute. Must be effective to maximum range at maximum altitude. Deployable on command from the GCS and by autopilot at any time during flight
- Real-time position and attitude data transmission to ground station
- Near real-time transmission of critical system parameters to ground station, including fault messages
- At least one forward facing wide-angle live video camera with real time transmission to GCS
- Inherently stable (self-righting) and easy to fly manually with standard RC equipment
- Suitable for reliable all-weather operations in Norway
- High-G tolerance, +/-16 G
- A compromise between the optimal thermal soaring and high-speed design.

A.2 Structural design

Wings and V-tail may be of a solid foam core sandwich type, with integrated wing spar and carbon/glass/abachi skins. Wing skins should have $\pm 45^\circ$ fibers to provide high torsional stiffness for high V_{ne} (never-exceed velocity). Finish may be acrylic spray-paint.

The control surfaces should be designed for high torsional stiffness to prevent flutter, which also ensures a high V_{ne} .

The fuselage will be a composite shell, similar to full-size sailplanes. A foam sandwich construction in either fiberglass fabric/aramid paper or fiberglass/carbon fiber fabric with vacuum bagging may be used.

A.3 Communications systems

Communications requirements will include telemetry, command and control and payload data. Data-links are recommended (in STANAG 4586 (33)) to comply with STANAG 7085 (33), which specifies the physical characteristics of the data link system. The data content is specified in other STANAGs referenced in STANAG 4586. In the long term, compliance with STANAG 7085 (or any follow-on standard) should be sought.

In the short term, low cost, low data rate, low power solutions should be sought without regard to military interoperability or performance beyond the strictly necessary for development purposes. Future developments in communications technology will provide new opportunities (especially with regard to antennas and power amplifiers). Current systems in operational use should therefore not restrict the design of the SUAV demonstrator.

A.4 Airborne antennas

It requires careful design to make high frequency antennas work well on an aircraft. Instead of adding an antenna to an airframe, the airframe and antenna(s) should be designed together for optimum performance.

Aerodynamically it is a great advantage if antennas can be integrated in the airframe skin or placed inside the airframe. Most existing UAV designs simply add the antenna externally, accepting the fuel efficiency penalty.

An initial SUAV demonstrator should use simple omni-directional antennas integrated inside the airframe to reduce drag as much as possible. Airframe materials must not hamper signal propagation.

A.5 Control system

Initially, the demonstrator UAV will not be operated routinely in controlled airspace, or out of visual range. The first trials may be done with the aircraft in full remote control, as for any other model aircraft. However, an autopilot and sufficient means for communications must be incorporated in due time, as visual range (1-2 km) is probably too restrictive for full concept development.

To maximize flexibility and future potential, the SUAV control system should seek the highest possible level of NATO interoperability in the long term. STANAG 4586 specifies the general requirements for an interoperable UAV control system architecture. It refers to a number of other STANAGs with which the given subsystems should or must comply. The requirements

in STANAG 4586 should be studied, and implemented in the long term as resources allow. The ability to control the SUAV demonstrator from a standard GCS will be valuable, e.g. to compare the performance of the SUAV with another UAV type in simultaneous operations. In the short term, such STANAG compliance is not possible within a tight budget. Simple solutions based on common commercially available hardware and software (COTS) should be employed as far as possible. The desire to develop new capabilities results in a need for programmable control system elements.

A.6 Autopilot

A commercially available autopilot for model aircraft and UAVs, such as the Micro Pilot MP2028 (28) or the Cloud Cap Technology Piccolo (29) may be used for flight operations beyond visual range. These products include navigation, low data-rate communications and payload management functions. Waypoints can be programmed in advance and changed during flight. GPS is integral to both the MP2028 and the Piccolo. The Piccolo can be fully programmed by the user, whereas the MP2028 is probably less flexible. The cost of these units is currently about USD 5000 for the MP2028, and about USD 7000 for the Piccolo (in addition to ground station).

The applicability of these COTS autopilots to flying very close to the ground is uncertain. The safety performance of such systems should be explored.

A custom autopilot may have to be developed at some point (possibly based on a PC/104) to satisfy the demands of more advanced soaring algorithms.

A.7 Ground Control Unit

Most of the “intelligence” needed for an initial concept demonstration may be located in a manned facility. As several days of endurance is desired (during possibly harsh weather), the most practical solution would be a sheltered ground control station (GCS) with heating and air conditioning, where operators may work shifts. The GCS must be mobile, preferably implemented within a single terrain-capable vehicle. Possible future developments should allow operation of the SUAV demonstrator from a standard GCS, as will be supplied with an operational UAV system.

A.8 Propulsion and power

A demonstrator SUAV will require a constant power source for avionics and payloads, as well as intermittent power to propel the aircraft. Payload and control power will be guaranteed by a large capacity battery pack. Separate power systems for vital control functions and other components will increase safety.

Low altitude, low speed and long endurance all point towards an external propeller system. Slowly rotating, large diameter propellers mated to a piston engine is considered a reliable,

efficient, and low-cost solution in the short term. The engine must be coupled to a self-starter and an electrical power generator. These two functions may be combined in one single unit (where the starter is the “reverse” of the generator).

In the long term (e.g. for a future development based on the demonstrator), and for extreme endurance development, hybrid electric concepts should be looked into. The energy efficiency of electric motors is higher than internal combustion engines (90 % as opposed to 20 %). Batteries, fuel cells and solar cells are being improved rapidly. Solar cells integrated in the wing structures may be a valuable “bonus” in summertime operation (providing about 300 W at best from 2 m² wing area), but they will be useless much of the year in Norway. Such wings have been experimented with. Fuel storage is perhaps the main obstacle to short term use of fuel cells in aircraft. Projects are already underway in which fuel cells will be used in combination with batteries in manned motor gliders.

A.9 Breguet endurance equation

The power required for propulsion is:

$$P_R = DV_\infty$$

Power available for propulsion, P_A , must equal P_R for steady, level flight.

Due to losses in the propeller this power is smaller than the power delivered to the propeller, P :

$$P_A = \eta_p P$$

P = shaft brake power from engine [W], often denoted shp or bhp.

η_p = propeller efficiency [1]

P_A = power available for propulsion [W]

D = drag force [N]

E_f = specific fuel energy [J/kg]

η_e = engine efficiency [1]

V = velocity [m/s]

g = gravity constant (9,81 m/s²)

W = weight = mass x g [kg]

$$P = \frac{P_A}{\eta} = \frac{DV_\infty}{\eta}$$

$$D = L \left(\frac{D}{L} \right) = W \left(\frac{D}{L} \right)$$

$$E = \int_{W_1}^{W_0} \frac{dW}{cP} = \int_{W_1}^{W_0} \frac{\eta}{c} \frac{dW}{DV_\infty} = \int_{W_1}^{W_0} \frac{\eta}{c} \frac{L}{DV_\infty} \frac{dW}{W}$$

Given a constant angle of attack and airspeed, we have a simplified Breguet endurance equation:

$$E = \frac{\eta_p}{c_p} \frac{1}{V_\infty} \frac{L}{D} \ln\left(\frac{W_0}{W_1}\right)$$

Not assuming constant airspeed:

$$L = W = \frac{1}{2} \rho_\infty V_\infty^2 S C_L$$

$$V_\infty = \sqrt{\frac{2W}{\rho_\infty S C_L}}$$

Inserted in the integral, this gives:

$$E = \int_{W_1}^{W_0} \frac{\eta}{c} \frac{C_L}{C_D} \sqrt{\frac{\rho_\infty S C_L}{2}} \frac{dW}{W^{\frac{3}{2}}}$$

Assuming all factors constant except for the weight, we get:

$$E = \frac{\eta}{c} \frac{C_L^{\frac{3}{2}}}{C_D} (2\rho_\infty S)^{\frac{1}{2}} \left(W_1^{-\frac{1}{2}} - W_0^{-\frac{1}{2}} \right)$$

Using this version of the equation assumes a constant altitude and angle of attack.

A.10 Powered endurance calculations

To evaluate the two versions of the Breguet Endurance equations for the SUAV design, we need to estimate the values of η_p , ρ , c_p , L/D and the maximum value of $C_L^{3/2} / C_D$ with corresponding airspeed.

η_p , the propeller efficiency, is estimated to be 0,9. This assumes a rather large, geared propeller.

Density at sea level is (ICAO std atmosphere (32)) $1,2250 \text{ kg/m}^3$. Maximum endurance will be achieved by flying as low as possible. Density at 3000 m (normal TUAV altitude) is $0,9093 \text{ kg/m}^3$. This is a more practical average SUAV operation altitude.

The specific fuel consumption may be estimated using:

$$c_p = \frac{g}{E_f \eta_e}$$

E_f is the specific energy of the fuel, in this case 42 MJ/kg (petrol, 0,7 kg/l). Plugging in the numbers gives $c_p = 2,336e-6 \text{ N}_{\text{fuel}}/\text{Ws}$, corresponding to a time specific fuel consumption (with a brake power output of 245 W) of 2,055 $\text{N}_{\text{fuel}}/\text{hour}$ (0,209 kg fuel/hour, or 0,3 l fuel/hour).

The maximum power factor ($C_L^{3/2} / C_D$) and the corresponding lift coefficient (and thus airspeed) can be found from a plot for the specific airfoil chosen. For the HQ/W-1,5/12 (which may be chosen for the SUAV demonstrator) the maximum power factor is approximately 19, corresponding to an airspeed of 18 m/s.

Given a maximum fuel amount of 5 kg, the maximum endurance then calculates to 26,5 hours using the constant angle of attack and airspeed version, and 32,5 hours using the constant altitude version. This result is reasonable, as one should expect a longer endurance while flying low than high (when flying at a constant speed, the aircraft will climb as fuel is burned). An average endurance with 5 kg of fuel is rounded to 30 hours.

A.11 Power required for level flight

In level flight, maximum endurance is achieved by flying at the velocity for the best $C_L^{3/2} / C_D$. For the chosen profile, this occurs at about 18 m/s. The L/D at this speed is about 20. Using the formulas from the Breguet-section above:

$$P_A = DV_\infty$$

$$D = L \left(\frac{D}{L} \right) = W \left(\frac{D}{L} \right) = mg \left(\frac{D}{L} \right)$$

Plugging in the appropriate values, we get

$$P_A = 25 \text{ kg} \times 9,81 \text{ m/s}^2 \times 18 \text{ m/s} / 20 \text{ (L/D)} = 12.26 \text{ N} \times 18 \text{ m/s} = 220,7 \text{ W}$$

Assuming a propeller efficiency of 90 %, the required shaft power is $220,7 \text{ W} / 0,9 = \underline{245,25 \text{ W}} = \underline{0,33 \text{ hp}}$

In addition comes the power required for avionics and possibly battery charging simultaneously. This will probably amount to less than 100 W, or 0,134 hp, for the simplest version of an SUAV demonstrator without power-demanding high-rate telemetry.

A.12 Power required to climb

The power required to sustain a 1 m/s rate of ascent:

$$\text{Power} = W \times (\Delta h / \Delta t) \rightarrow 245,25 \text{ N} \times 1 \text{ m/s} = \underline{245,25 \text{ W}} = \underline{0,33 \text{ hp}}$$

A.13 Fuel calculation

The amount of fuel required to achieve 18 hours endurance can be found by solving the Breguet equation for W_0/W_1 and evaluating, using the appropriate (estimated) values. The result, using the version of the equation that assumes constant velocity and angle of attack, is about 3,5 kg of fuel.

A.14 Electrical power requirements

The following power requirements are based on experience with model aircraft. The power requirements for telemetry can only be roughly estimated at this time, based on an output of 100 mW (legal limit in the 2,4 GHz free band) and a transmitter efficiency of less than 10 %. The PC104 and autopilot power requirements are based on representative product data.

Equipment	Estimated current drain	Estimated power drain	Calculated energy for 72 hours operation
8 actuators	800 mA	$0,8 \text{ A} \times 5,0 \text{ V} = 4,0 \text{ W}$	829 440 J
Receiver	50 mA	$0,05 \text{ A} \times 5,0 \text{ V} = 0,25 \text{ W}$	64 800 J
Sum rc-equipment	850 mA	$0,85 \text{ A} \times 5,0 \text{ V} = 4,25 \text{ W}$	1 101 600 J
Telemetry	300 mA	$0,3 \text{ A} \times 5,0 \text{ V} = 1,5 \text{ W}$	388 800 J
Autopilot (including GPS)	150 mA	$0,150 \text{ A} \times 5,0 \text{ V} = 0,75 \text{ W}$	194 400 J
PC104	320 mA	$0,320 \text{ A} \times 5,0 \text{ V} = 1,6 \text{ W}$	414 720 J
Sum telemetry/autopilot	770 mA	$0,77 \text{ A} \times 5,0 \text{ V} = 3,85 \text{ W}$	997 920 J
Total	1620 mA	$1,620 \text{ A} \times 5,0 \text{ V} = 8,1 \text{ W}$	<u>2 099 520 J</u>

A.15 Batteries

The requirements are for 54 hours battery power duration. The other 18 hours are to be supplied by the engine-driven generator. A margin of 25 % (18 hours) is even so added to the 54 hours, resulting in 72 hours electrical power supply from batteries. Given a specific energy of 576 MJ/kg for Li-Ion cells, $2,1 \text{ MJ} / 0,576 \text{ MJ/kg} = 3,645 \text{ kg}$ of batteries. This corresponds to 94 cells.

A.16 Specifications

The following table summarises the characteristics of the demonstrator SUAV. It must be emphasised that this is not yet a thoroughly worked-through design. Important parameters have been estimated, and the design will need further adjustments. It will not be possible to ascertain many of the actual weights, dimensions and performance figures until the aircraft is actually built.

Dimensions**Wings**

Wing span	500 cm
Chord (root/middle/tip)	45/30/15 cm
Wing area	185 dm ²
Elevator area	0,25 dm ²
Airfoil	HQ/W-1,5/12
Aspect ratio	13,5

Fuselage

Length	280 cm
Fuselage diameter	31 cm
V-tail angle	90°

Weight

Max take-off weight	25 kg
Wing loading @max TOW	135 g/dm ²
Min take-off weight	18 kg
Wing loading @min TOW	97,3 g/dm ²
Airframe only	8 kg
Actuators weight	6 x 95 g + 2 x 55 g = 710 g
Retractable landing gear	700 g
Engine w/generator + starter	1000 g
Autopilot	300 g
Telemetry	3000 g
Fuel (petrol)	3500 g
Batteries	3645 g
Total without payload	20 855 g
Payload weight/additional batteries/fuel/other	4145 g

Actuators

Type	Multiplex Digital
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Propulsion

Engine type	Internal combustion, 1 cylinder, w/generator and self-starter
Propeller type	Folding, large diameter, geared
Propeller efficiency	0,9
Engine efficiency	0,1
Required output shaft power for level flight	245,2 W (0,33 hp)
Required total shaft power including 1m/s climb ability	490,5 W (0,66 hp)
Estimated power specific fuel consumption	2,33e-6 N/Ws (0,21 kg/hour)

Performance

Reynolds number in cruise	470000
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Best glide (L/D)	20
$C_L^{3/2} / C_D$ max	18
Best glide angle	3°
Glide velocity	19 m/s (68km/h)
Endurance cruise speed	18 m/s (65km/h)
Minimum rate of sink	0,9 m/s
Stall speed @18/25 kg	35/45 km/h
Max airspeed	160 km/h
Total avionics power endurance	72 hrs
Engine power endurance, 3,5 kg fuel	18 hrs
Engine power endurance, 5 kg fuel	30 hrs

A.17 Cost

The following is a cost estimate for the SUAV demonstrator airframe based on experience with large-scale sailplane models. The estimate does not include man-hours, consulting fees or ground support equipment. These costs may amount to several times that of the airframe itself.

Materials for the fuselage mould and the fuselage itself	NOK 30 000
Wing sections	NOK 20 000
Engine (e.g. 4-stroke, 1-cyl, EFI.)	NOK 10 000
Actuators, batteries and other accessories	NOK 20 000
Autopilot (e.g. MP2028/Piccolo)	NOK 50 000
Tools, chargers and transmitters	NOK 10 000
PC104	NOK 10 000
TOTAL for one aircraft	NOK 150 000

B APPENDIX. ACRONYMS

COTS	Commercial Off The Shelf
DNMI	Det Norske Meteorologiske Institutt (The Norwegian Meteorological Institute)
DS	Dynamic Soaring
G	Gravitational acceleration
GCS	Ground Control Station
GIS	Geographical Information Systems
GPS	Global Positioning System
HIRLAM	High Resolution Limited Area Model
Li-Ion	Litium Ion
INS	Inertial Navigation System
MACWAVE	Mountain and Convective Waves Ascending Vertically
MALE	Medium Altitude Long Endurance
METOC	Meteorology and Oceanography
MWFM	Mountain Wave Forecast Model
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organisation
NOK	Norwegian Krone
NRL	Naval Research Laboratories
OSTIV	Organisation Scientifique et Technique du Vol à Voile
REA	Rapid Environment Assessment
SMHI	Sveriges Meteorologiska och Hydrologiska Institut
SUAV	Soaring Unmanned Aerial Vehicle
TUAV	Tactical Unmanned Aerial Vehicle
UAV	Unmanned Aerial Vehicle
USD	United States Dollar
SINTEF	Selskapet for Industriell og Teknisk Forskning ved Norges tekniske høgskole (The Foundation for Industrial and Scientific Research at the Norwegian Institute of Technology)
STANAG	Standardization Agreement
Vne	Velocity, Never Exceed

LITTERATURE AND REFERENCES

- (1) Anderson J D Jr. (1989): Introduction to Flight, 3'rd edition, McGraw Hill.
- (2) Beer T (1974): Atmospheric Waves, Wiley & Sons.
- (3) Eidsvik K J, Holstad A, Lie I, Utnes T (2003): A Prediction System for Local Wind Variations in Mountainous Terrain, DNMI report in publication.
- (4) Gossard E E, Hooke W H (1975): Waves in the Atmosphere, Developments in Atmospheric Science 2, Elsevier.
- (5) Handbook of meteorological forecasting for soaring flight, World Meteorological Organization Technical note No.158. 2.nd ed.1993.
- (6) Lie I (2001): Wind Conditions in Fjærlandsfjorden, DNMI report.
- (7) Nordeng T E, Lie I et al: Mehamnulykken. En vurdering av de meteorologiske forholdene i lys av modellsimuleringer. DNMI report.
- (8) Palmer, M (1989): Practical Wave Flying, Revised Edition, Lenticular Publishing.
- (9) Reichmann, Helmut; Cross-Country Soaring, Thomson, 1978.
- (10) The Soaring Society of America, Inc (1976): Soaring Meteorology for Forecasters, 2.nd edition.
- (11) Whelan, R F (2000): Exploring the Monster. Mountain Lee Waves: The Aerial Elevator, Wind Canyon Books.
- (12) Østbø, M (2003): Unmanned Aerial Communications Platforms, FFI/RAPPORT-2003/00423, Norwegian Defence Research Establishment.
- (13) http://www.wfu.edu/albatross/atwork/dynamic_soaring.htm
- (14) <http://members.tripod.com/douglasturner/id27.htm>
- (15) http://www.charlesriverrc.org/articles/flying/markdela_ds.htm
- (16) <http://www.iggnorge.com>
- (17) <http://www.mountain-wave-project.de>
- (18) <http://www.uap-www.nrl.navy.mil/dynamics/html/mwfm.html>
- (19) <http://www.uap-www.nrl.navy.mil/dynamics/html/norwayclim.html>
- (20) <http://www.ssc.se/esrange/campaigns/macwave.shtml>
- (21) <http://www.firnspiegel.com/Perlan>
- (22) <http://www.lange-flugzeugbau.com>
- (23) <http://www.insitugroup.net>
- (24) <http://www.aerosonde.com>
- (25) <http://www.boeing.com/defence-space/military/unmanned/scaneagle.html>
- (26) <http://www.smhi.se>
- (27) <http://www.wavecamp.no>
- (28) <http://www.micropilot.com>
- (29) <http://www.cloudcaptech.com/piccolo.htm>
- (30) <http://www.stemme.de>
- (31) <http://www.sintef.no>
- (32) <http://www.icao.org>
- (33) <http://www.nato.int>
- (2) <http://www.saftbatteries.com>