DEVELOPMENT AND FLIGHT TESTING OF AN AUTONOMOUS PARAFOIL-LOAD SYSTEM DEMONSTRATOR

Thomas Jann
German Aerospace Center (DLR)

Keywords: *parafoil, GNC, autonomous landing, flight testing*

Abstract

The Institute of Flight Systems of the German Aerospace Center (DLR) developed the low-cost technology demonstrator ALEX (Small Autonomous Parafoil Landing Experiment) in order to identify the dynamic behaviour of a parafoil load system and to investigate GNC concepts for the autonomous landing of space capsules and precision airdrop using gliding parachutes.

The paper gives an overview about the development of the experimental vehicles and presents details about the GNC algorithms, particularly the unique "T-Approach" guidance strategy developed by DLR. The paper is completed by giving results from the flight tests, which demonstrated the capability of landing about 50 m close to the predefined target point.

1 Introduction

Because of their capability of wind penetration and precise landing aerial delivery and recovery of payloads using gliding parachutes have been subject to several investigations [eg. 1-6]. In Germany, the Institute of Flight Research of DLR has developed and flight tested two instrumented test vehicles ALEX-I and -II (Small Autonomous Parafoil Landing Experiment) of about 100 kg payload each. The small size and weight of the vehicles allows using personnel ram air parachutes and help to keep the costs of flight testing low.

Unmanned payloads like cargo systems require either a remote pilot or an autonomous methodology to guide the vehicle to its predefined target. The design philosophy of the developed "T-Approach" focuses on a simple and robust algorithm which is easy to adapt to different vehicle and environmental characteristics.

Understanding the vehicle flight mechanics and the aerodynamics of the gliding parachute is necessary for modeling the system. The acquired flight test data led to a database which was used for the determination of the aerodynamic characteristics of the ALEX vehicle applying system identification methods. The implementation of an accurate mathematical model into a simulation environment allowed reliable testing of GNC algorithms prior to flight.

2 ALEX System

Due to limited resources and because of the relatively high risk of damage in parachute drop tests, not only the capsule but also the instrumentation was made using low cost off-the-shelf hardware. These days, as a result of the progress in electronic miniaturization and hardware development, many sensors from the consumer sector provide high performance quality. However, they are still not commonly used in avionic systems. Accordingly, there was very little experience with them in the Institute of Flight Systems. It turned out that most of the sensors used worked well. However a few sensors showed characteristics that needed special treatment (e.g. filtering).

2.1 ALEX Basic Vehicle

The nominal vehicle weight of 100 kg was selected for practical reasons: 100 kg can still be handled by four men without a crane and be shipped in a small truck. Also an inexpensive personnel parafoil can be used. The test vehicle is made from standard aluminum profiles and plain sheets. No effort was made to manufacture an expensive low drag shape. The payload drag is anyway only in the order of 5% of the total drag. If the payload drag could be reduced by 40%, the total drag would decrease by only 2%, resulting in a 2% increase of the glide ratio.

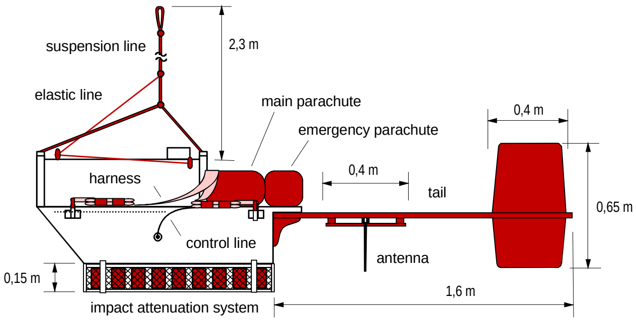

Fig. 1. ALEX basic vehicle

The main parachute system consists of a Parafoil 252-7 lite that is activated by a retractable static line. The static line pulls a packsack with a pilot chute from the parachute pack. The pilot chute deploys the parafoil, which is reefed by a slider. For emergency cases a stable cross type parachute is available. It will be initiated by a standard Cypres device if the rate of descend increases above 13 m/s below 250 m altitude. As impact attenuation system a sandwich construction was used, which consists of two plywood panels and in between a flat block of plastic foam containing holes to insert empty soft drink cans.

ALEX Basic Vehicle	
Capsule	140 x 50 x 55 cm
Actuator System	DC gear motors
Damping Device	100 x 50 x 15 cm
Tail Fin	160 cm, 40 x 65 cm
Main Parachute	Parafoil 252-7 lite
Emergency Parachute	Hoenen STK-7.2m-12
Total Mass	104 kg

Tab. 1: ALEX Basic Vehicle

A tail fin was applied to stabilize the vehicle and prevent yawing during the transfer flight beneath the helicopter towards the air release point. However, in some cases a low-damped and coupled pendulum oscillation about the roll- and yaw-axis was encountered when the helicopter was approaching the drop point and reduced speed from 60 to 20 kts. This could be avoided by elongating the tail from formerly 140 to 160 cm and keeping the helicopter speed at about 60 kts during release.

Fig. 2. ALEX vehicle beneath helicopter

For steering the parafoil via the control lines, the vehicle contains two DC motors with gearboxes that are connected to an analog actuator control unit. This unit contains a command converter that allows switching between manual remote control and autonomous control, the last with commands coming from the on-board computer. In case the vehicle gets out of reach for the remote control, a fail-safe mode has been included that pulls the control lines to an asymmetrical deflection. Batteries are combined in a powerpack providing the actuators and electronic devices with ±24, ±12 and 8/14 V.

2.2 ALEX Instrumentation

The vehicle is equipped with a PC compatible on-board computer (OBC). To its interface additional modules for analog data acquisition and serial interfacing are connected. Together with a ruggedized hard disc and a power regulating unit the on-board computer is integrated into a small housing. A 433 MHz radio modem works in semi-duplex mode and provides a wireless bi-directional communication link to the ground station [7].

The inertial sensor set consists in MEMS accelerometers from Analog Devices and micromechanical rate gyros from Murata, each in a three-axial assembly. Also a three-axis magnetometer from PNI is used to provide additional attitude information. Two separate GPS receivers are installed, one working in regular GPS-mode (Garmin GPS36) and the other in DGPS-mode (Trimble Lassen SK8).

The airflow is measured using a 0.8 m long noseboom. It is equipped with a Pitot-tube and two vanes to measure angle of attack and angle of sideslip. Because no practical method was found that would allow protecting the noseboom reliably from damage, it was decided to design the noseboom as simple as possible and to dispose it after the flight. The dynamic pressure is piped through plastic tubes to a differential pressure sensor inside the capsule. The vanes are connected to contactless magnetoresistive potentiometers.

A Jenoptik laser altimeter was installed to enable correct flare initiation in autonomous mode. An absolute pressure sensor for barometric altitude, an air temperature sensor and actuator position transducers are completing the sensor set. Force transducers for measuring the suspension and shock loads are prepeared but have not been used up to now.

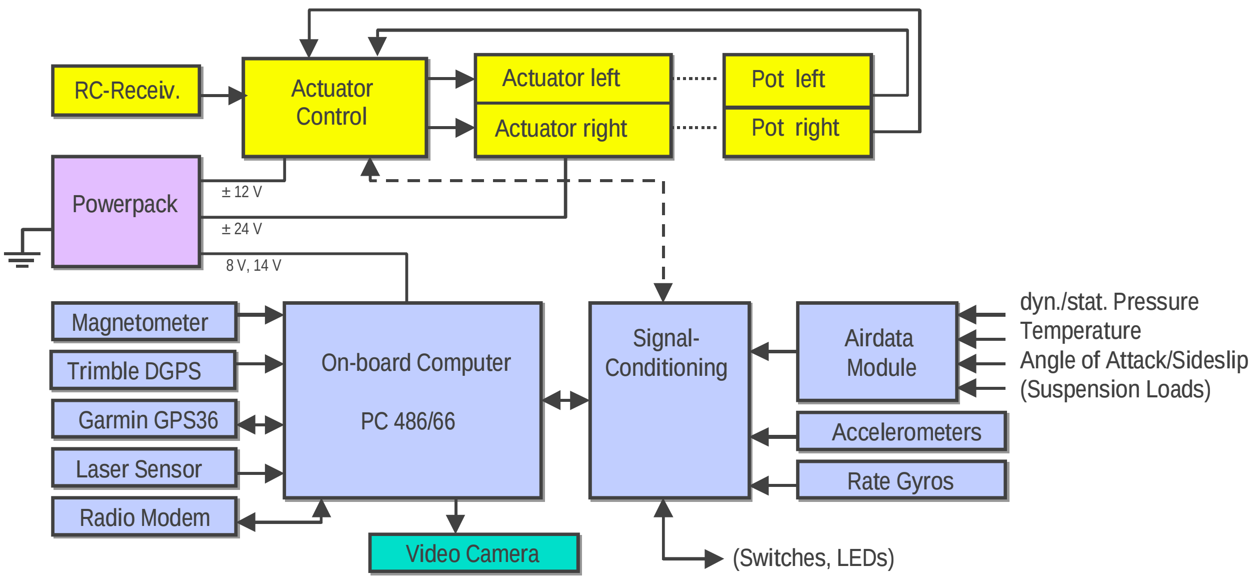

Fig. 3: Electrical concept for ALEX system

On-board computer, most sensors, radio modem and other electronic modules are installed on a removable platform that can easily be exchanged between both vehicles. The platform is mounted on shock absorbing devices and located in the upper part of the vehicle, where it can be accessed through a window in the front. If needed, also other instrumentation packages (e.g. from industry) can be prepared independently on another equally sized platform and be installed in the vehicles. Magnetometer, GPS-receiver and antennas are installed on the tail. Figure 3 gives an overview about the electrical concept.

The vehicle is also equipped with an upwards looking video camcorder that records a video of the apparent motion of the canopy during flight. For post-flight analysis this video is digitized and loaded into an application that is capable of tracking features of the canopy throughout the entire video sequence. Multiple point tracking gives a deep insight into relative positions, velocities, and angles between parafoil and load.

The ground station provides a bi-directional radio modem link to the vehicle. On ground a first notebook PC (GPC) collects all the received telemetry data and is used as terminal for telecommands to the ALEX OBC. Some of the telemetry data is transferred to a second notebook that serves as 'on-line track display' (OTD) for the ground crew to follow the actual trajectory of ALEX in flight (Fig. 4).

OBC- and GPC-software is based on the real-time operating system RT-Kernel. During flight the acquired data is written on the hard disc and also partly transmitted to the ground station via telemetry. After each experiment the flight test data is extracted and converted to ASCII-files for the following post flight analysis.

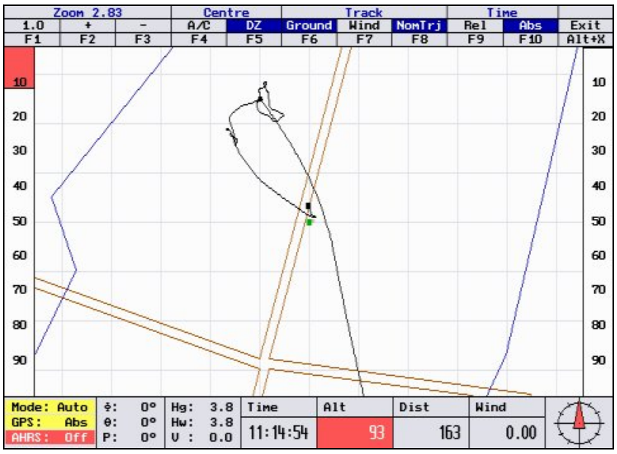

Fig. 4. On-line track display (OTD)

3 GNC for Autonomous Landing

In contrast to powered vehicles, gliding parachutes usually don't have the ability to ascend, and thereby a second chance for the landing approach is not given. Standard glide ratios of such systems are normally much too small to utilize thermal lift, hence flying distance and the area of accessible landing sites are limited. Also, the low speed compared to conventional aircraft makes such systems very susceptible to wind. Thus, first of all, altitude and position of the air release point have to be chosen carefully to ensure that the landing point lies within this area.

The main task of the autonomous guidance, navigation and control (GNC) algorithm or simply the 'autopilot' consists in generating and making the vehicle follow a trajectory that guides the system to its predefined target. Because of uncertainties especially concerning the wind influence, GNC must be robust and capable to cope with unforeseen deviations from the planned trajectory. This robustness is best achieved by keeping reserve for corrections as long as possible.

The applied tasks traditionally are divided into three parts: guidance, navigation and control (GNC). The navigation task manages the data acquisition, processes the sensor data and provides guidance and control with information about the system states. Using this information along with other available system data, the guidance plans the mission and possible trajectory to fly from the actual position to the desired landing point. The guidance, located in the outer loop, produces the input for the subsequent control task that cares for appropriate actuator commands in the inner loop [8].

3.1 Guidance

For non-powered parafoil vehicles with almost constant glide ratio the reachability of the landing point can be represented by a cone, with a slope that corresponds with the glide ratio of the vehicle (Fig. 5). The closer the vehicle comes to the middle of the cone, the more reserve is available that can be utilized for trajectory planning. In contrast, if the vehicle is situated close to the edge of the cone, the landing point can only be reached by a straight forward glide.

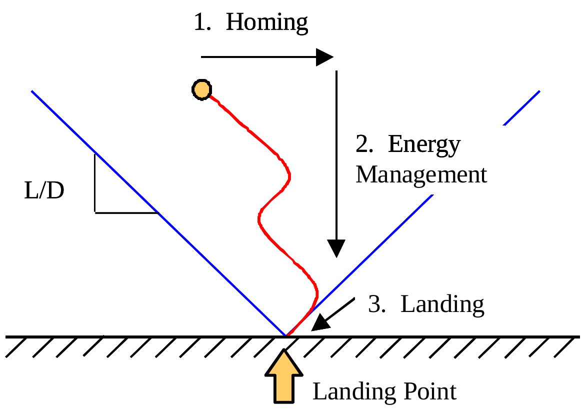

Fig. 5. Three guidance phases

Within this GNC concept, the guidance itself is divided into 3 phases: homing, energy management and landing. Homing, that is simply speaking, flying towards the landing site, i.e. towards the middle of the cone, maximizes the reserve. In this area the reserve equals the altitude that has to be reduced by the following energy management. During this second phase the trajectory must be planned in a way that the vehicle finally reaches the correct position for the landing approach. In order to land straight against the wind, an additional position offset must be foreseen.

Energy management for example can consist in flying circles and spiraling slowly down. This procedure is very effective, because only little control activity is required. Adaptation of the planned trajectory can be done by adjusting the circle radius [3-6]. This method works well for large circles and vehicles coming from high altitudes, but in lower altitudes it may have a problem in compensating deviations from the planned trajectory. Because the circle radius cannot be reduced below a certain value depending on the size and characteristic of the vehicle, it must be ensured that the circle can be completed before entering it. Hence, the guidance can get into a situation in which it is difficult to decide whether a complete circle shall be appended or not. If the decision is yes, the reserve for corrections is heavily diminished, if the decision is no, the remaining altitude must be reduced in a different way.

Another way of planning a trajectory is realized within the so-called ‘T-Approach’ that was developed by the Institute of Flight Systems of the German Aerospace Center (DLR). Based on the actual position and the available information the nominal trajectory is continuously updated until landing. By this means, deviations due to unknown wind and uncertainties in the system parameters can be compensated. The continuous process implies that steady changes in the actual position must result in steady changes in the planned trajectory and the generated commands. Otherwise decision ambiguities cannot be excluded. Instead of using circles, waypoints are distributed along a ‘T’-shaped pattern leading to the flight distance that is needed for reducing the surplus altitude (Fig. 6).

For wind accommodation, the trajectory is planned in the wind fixed coordinate system. The actual position of the used wind fixed frame is shifted to a virtual position by the predicted wind drift during the remaining flight until touch down.

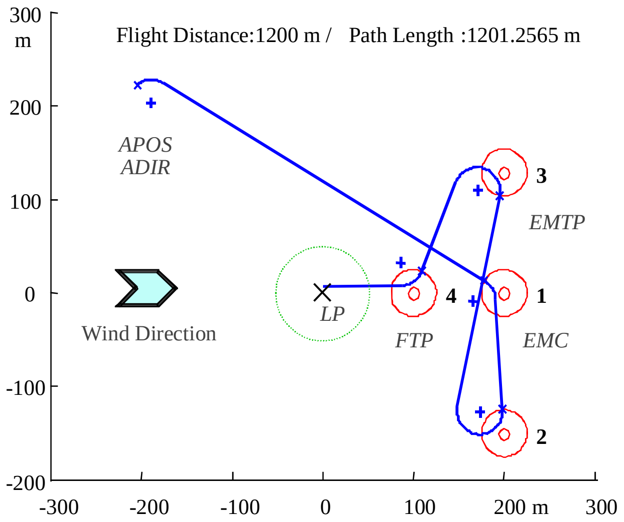

Fig. 6. ‘T-Approach’ guidance concept

The three guidance phases work as follows:

Homing: From the actual position (APOS) the energy management center (EMC) is approached if possible. If the remaining distance is not long enough to reach afterwards the landing point (LP), waypoint 1 is moved in direction to the final turn point (FTP). If altitude and subsequently remaining distance are still too small to reach the landing point, backup mode is entered.

Energy Management: After reaching EMC, surplus altitude is reduced by flying S-patterns to the energy management turn points (EMTP). If the remaining distance becomes too small to reach LP, the EMTP is shifted along the energy management axis towards the EMC.

Landing Approach: The landing phase is divided into 4 sub-phases: (1) transition into landing corridor, (2) approach of final turn point (FTP), (3) turn into wind and (4) flare.

Backup mode: The vehicle keeps heading the FTP until a specified decision altitude is reached. Then the vehicle turns against wind independently of its position and prepares for landing.

Starting point for the computation of the waypoint configuration and the belonging nominal trajectory is the remaining altitude above the nominal landing point. Assuming a constant mean glide ratio, the altitude can be transformed into a remaining flight distance that must equal approximately the sum of straight or curved segments the nominal trajectory is composed of. During trajectory planning the waypoint configuration is varied iteratively until this condition is fulfilled.

The waypoints (WP) are numbered in the order of their approach. Their positions determine the direction and distance the vehicle has to fly. Reaching a specified area around the aimed waypoint, the heading is changed in order to approach the next one. The guidance output is the commanded heading computed from the direct connection between the actual position and the next waypoint.

3.2 Navigation and Control

The navigation task provides guidance and control with processed sensor information. Position, altitude, speed over ground and course are taken from GPS. Since selective availability has been switched off in May 2000, plain GPS data without differential corrections was considered to be accurate enough for trajectory planning. For control also the heading or azimuth of the vehicle is needed.

Although the compass sensor provides good heading information during steady flight, it is unreliable during turn maneuvers with larger bank angles. This problem was solved by applying a complementary filter to compass azimuth and yaw rate [10].

Because the vehicle is stable in its entire flight envelope and uses only two control surfaces, the control demands are low and a simple approach could be selected for the control task.

The commanded heading is compared to the actual azimuth giving the amount of error the controller has to reduce. Depending on the sign of the heading error, either the left or the right actuator is activated, leading to a left or a right turn. As output the desired actuator position is computed by a saturation limited proportional controller.

3.3 Simulation

In order to evaluate the effects of parameter changes, unknown winds and sensor errors, simulation studies have been performed. For this purpose, the guidance and control algorithms were connected with an identified 4-DoF model of the parafoil-load vehicle forming the closed GNC control loop (Fig.7) [8].

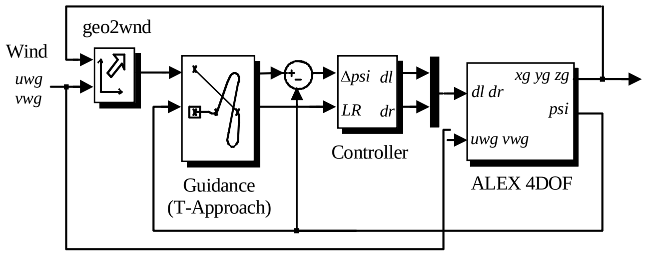

Fig. 7. GNC simulation block diagram

The simulation of the overall system including GNC is done in the MATLAB/Simulink environment. This allows transferring the identified models into simulation easily, exchanging them and comparing the results. Also effects of parameter changes, unknown winds and sensor errors can be studied, giving information about the quality and robustness of the GNC concept.

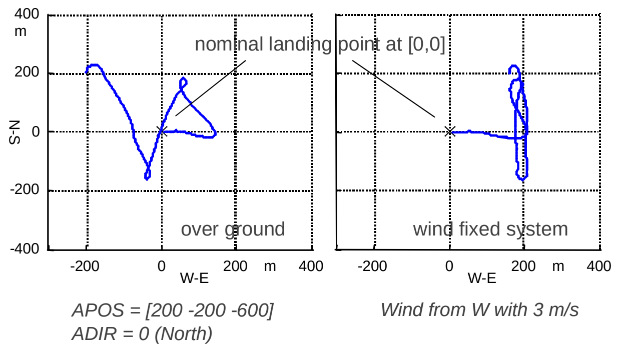

Fig. 8. GNC simulation results

The simulation results prove that possible wind mispredictions causing deviations from the flight path have more influence on the landing accuracy, than incorrect estimates of model parameters and measurement errors. However, correct information about position, altitude and especially heading is essential for precise landing. As long as the errors stay in the normal range (position ±10m, altitude ±5m, heading ±10°) the GNC algorithm is robust enough to land the vehicle within a range of ±50m around the predefined landing point, provided that the wind is perfectly known. Even the GPS time delay of about 1.8 sec is not a problem.

The simulation also has shown that the waypoint distribution should be updated at least every 2 seconds. Longer intervals cause sudden changes in the commanded heading and lead to a degradation of the system behavior and landing accuracy.

3.4 On-board Wind Estimation

One problem is the wind, or to be more precise, to know the actual wind profile accurately. Since wind drift is computed by integrating the wind profile over the remaining flight time, correct assumptions about the wind are crucial for the landing precision. This issue becomes more important the higher wind speed and altitude are.

However, accurate wind data is difficult to obtain in advance. To be independent of measurements prior to the flight and to avoid an active data link, it is possible to do an on-board wind estimation with a reasonable extrapolation of the profile until touch down. Remaining uncertainties in the estimated profile can be compensated by the adaptive trajectory planning.

The classical method consists in computing the current wind vector by subtracting the air speed vector $\mathbf{V}_a$ from the flight path velocity vector $\mathbf{V}_k$. The flight path velocity vector is available from GPS, the azimuth can be measured by an electronic compass (in combination with yaw gyro and complementary filter), and the air speed that can be measured using a pitot tube or a towed air data probe. Because gliding parachutes are approximately flying with constant air speed, instead of measuring a constant parameter can be used. However, if this parameter is very inaccurate, the estimated wind drift will also be incorrect compromising the landing precision.

For estimating a constant wind profile from turbulent environment and noisy measurements, the recursive mean value of the wind components is computed. Figure 9 shows as an example the true and estimated wind components for one simulated flight.

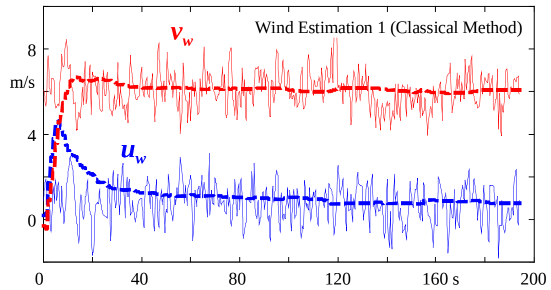

Fig. 9. True and estimated wind components from GPS and compass measurements

Until now, the sink rate w_g that is required for GNC calculations was supplied as predefined parameter. On the other hand, this parameter can be approximated easily from GPS measurements using recursive mean value, and, utilizing the provided air speed, the glide ratio L/D can be roughly estimated.

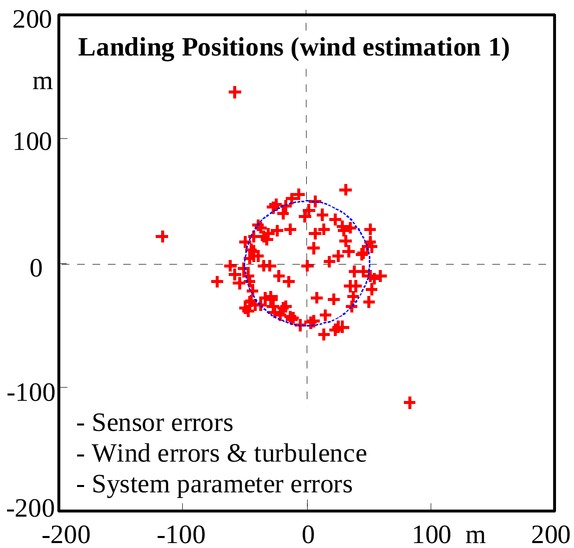

Fig. 10: Monte-Carlo analysis

All together, the described wind computation and the estimation of the two parameters w_g and L/D were integrated into the GNC algorithm, preceding wind accommodation and guidance. Taking into account sensor, wind and parameter errors and turbulence a landing accuracy of about 50 m could be obtained from Monte-Carlo analysis (Fig. 10) [10].

4 Flight Tests

Up to now, 24 flight tests have been conducted in total. Flight tests #1 to #12 were remotely controlled and served mainly for system development and flight data acquisition. Flight tests #13 to #24 were used to test the autonomous landing and for more sophisticated data acquisition (incl. video of the canopy for relative motion analysis, introduce maneuvers for system identification).

Flight tests were conducted by dropping the vehicle from altitudes between 600 to 2000 m above ground according to the available safety area. From the last twelve flight tests, seven landed autonomously, two were dedicated to data acquisition and three tests suffered from malfunctions. These malfunctions were caused during the parachute deployment phase and prevented nominal control.

Fig. 11: ALEX vehicle in flight

Before flight testing, the GNC algorithm was integrated in the existing OBC software.

While navigation and control task are executed in real-time with 10 Hz frequency, the guidance task stays in background and is triggered every second (1 Hz), providing the waypoint update. Several hardware-in-the-loop tests have been conducted, proving the algorithms to work also in the final hardware environment. Because in this test the vehicle did not move, the motion was simulated in the GPC and sent by radio modem to the OBC in the vehicle.

During flight, the autonomous mode can be activated and deactivated by the remote control on ground. This allows taking over control manually whenever necessary.

4.1 Some Results from Flight Testing

As an example, the following figures present the results of a successful autonomous landing about 30 m close to the target. Fig. 12 shows the trajectory above ground, Fig. 13 shows the same trajectory transformed into the windfixed coordinate system.

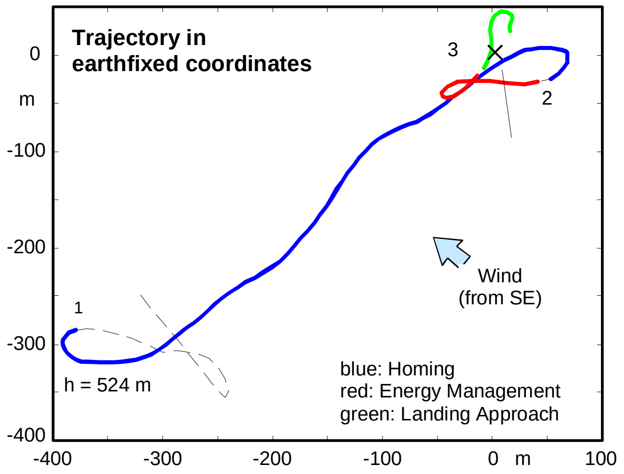

Fig. 12: Trajectory above ground

The vehicle first flies in homing mode (phase 1, blue) towards the EMC, enters then the energy management mode (phase 2, red) and shortly after this to the landing approach (phase 3, green). In an altitude of 20 m above ground the control lines were both pulled symmetrically to perform a soft landing.

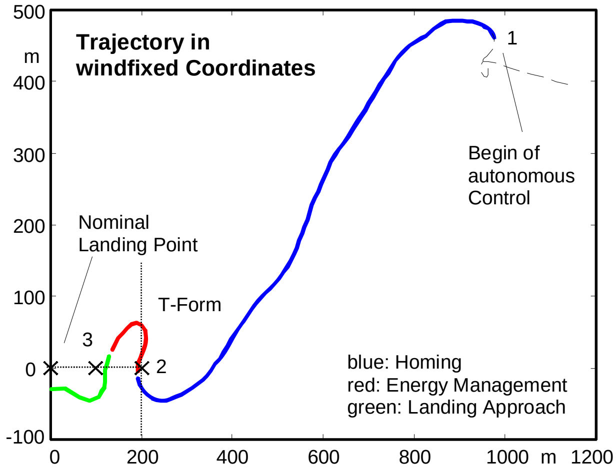

Fig. 13: Trajectory in windfixed coordinates

Towards the end of the homing phase there is a small driftage from the nominal flight path that leads the vehicle first to pass the EMC and then turn back towards it. This is mainly due to errors in the wind estimation that cannot follow a sudden deviation of windspeed and -direction appearing in about 120 m altitude (Fig. 14).

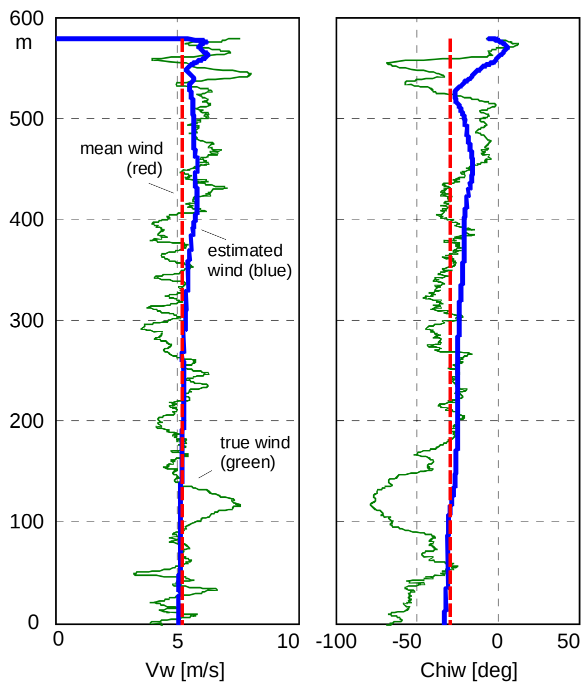

Fig. 14: True and estimated wind profile

Figure 15 shows the time histories of the same flight for true and commanded heading and left and right actuator position. Since the control line force acts like a disturbance variable in the actuator control loop, there remains small control offset between commanded and true actuator position. The offset in the heading control loop results primarily from the progressive characteristic of the nonlinear control efficiency, which is caused by the flexibility of the parafoil wing and their trailing edge flaps. In combination with the proportional controller in the heading control loop small errors in the heading are not compensated entirely.

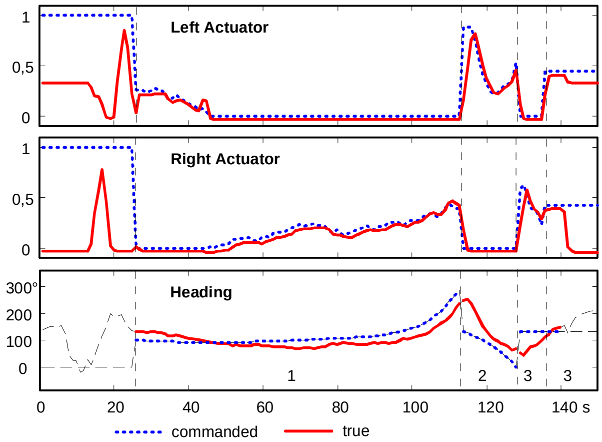

Fig. 15. Commanded and true values for actuator position and heading

4.2 Nonlinear control efficiency

The acquired flight test data led to a database which was used for the determination of the aerodynamic characteristics of the ALEX vehicle applying system identification methods. Prior to aerodynamic parameter identification, a flight path reconstruction identifies sensor scaling factors and offsets and ensures data compatibility.

Longitudinal and lateral flight dynamics have been analyzed and incorporated into mathematical models of different complexities. In a corresponding simulation environment reconstructed trajectories of flight tests showed a good match with the real flight trajectory. In order to get the actual motion of the canopy, the measurements are transformed from the capsule to the parafoil taking into account the relative motion between both, obtained by video analyzing techniques.

An important point for model improvement was the introduction of a nonlinear control efficiency that helped to model the effects of canopy deformation due to control surface deflections [9].

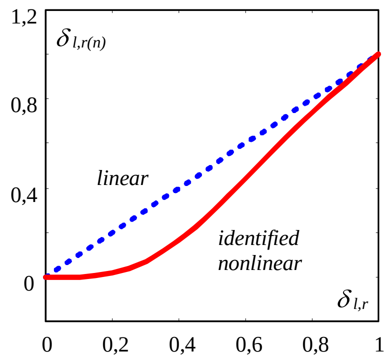

Fig. 16. Nonlinear control efficiency

One result of the system identification was the progressive characteristic for the nonlinear control efficiency (Fig.16). This means that small control line deflections apparently are absorbed by the flexibility of the canopy until larger deflections lead to a significant increase of the local drag. However, the characteristic depends not only on the canopy design but also on the trim of the control lines that again may be subject to change between different configurations of the same parafoil. The other way round this also means that the canopy and hence the parafoil system will react faster, if the control lines are trimmed in a 20% to 40% position.

5 Conclusion

The paper gives an overview about the development of the experimental vehicle ALEX and about the GNC algorithms, particularly the unique “T-Approach” guidance strategy developed by DLR. The paper is completed by giving some results from the flight tests, which demonstrated the capability of landing about 50 m close to the predefined target point.

The last flight tests have been conducted in August 2005. The GNC algorithm proved its capabilities and is ready to be adopted for operational systems. Research is now focusing on low-cost navigation, fault tolerant control and improved modeling and simulation of general parachute-load systems.

References

[1] Hattis, P.D., Benney, R., Demonstration of Precision Guided Ram-Air Parafoil Using GPS/INS Navigation, *Annual Meeting Proceedings, Institute of Navigation*, Cambridge, Massachusetts, June 19-21, 1996, pp 185-194

[2] Petry, G., Hummeltenberg, G., Tscharntke, L.: The Parafoil Technology Demonstration Project, P*roceedings of the14th AIAA Aerodynamic Decelerator Systems Conference*, San Francisco 1997, AIAA-Paper No. 97-1425

[3] Machín, R.A. et al: Flight Testing the Parachute System for the Space Station Crew Return Vehicle, *Journal of Aircraft*, Vol.38, No.5., pp 786-799, 2001

[4] Dellicker, S., Benney, R., Brown, G. Guidance and Control for Flat-Circular Parachutes, *Journal of Aircraft*, Vol.38, No.5., pp 809-817, 2001

[5] Wegereef, J., Jentink, H. SPADES: A Parafoil Delivery System for Payloads until 200kg, P*roceedings of the17th AIAA Aerodynamic Decelerator Systems Conference*, Monterey 2003, AIAA-Paper No. 2003-2110

[6] Krenz, H., Burkhardt, O. The FASTWing Project - A Self Navigated Gliding System for Heavy Loads, P*roceedings of the18th AIAA Aerodynamic Decelerator Systems Conference*, Munich 2005, AIAA-Paper No. 2005-1600

[7] Jann, T., Doherr, K.-F., Gockel, W.: Parafoil Test Vehicle ALEX – Further Development and Flight Test Results, P*roceedings of the15th AIAA Aerodynamic Decelerator Systems Conference*, Toulouse 1999, AIAA-Paper No. 99-1751

[8] Jann, T.: Aerodynamic Model Identification and GNC Design for the Parafoil-Load System ALEX, P*roceedings of the16th AIAA Aerodynamic Decelerator Systems Conference*, Boston 2001, AIAA-Paper No. 2001-2015

[9] Jann, T.: Aerodynamic Coefficients for a Parafoil Wing with Arc Anhedral – Theoretical and Experimental Results, P*roceedings of the17th AIAA Aerodynamic Decelerator Systems Conference*, Monterey 2003, AIAA-Paper No. 2003-2106

[10] Jann, T.: Advanced Features for Parafoil Guidance, Navigation and Control, P*roceedings of the18th AIAA Aerodynamic Decelerator Systems Conference*, Munich 2005, AIAA-Paper No. 2005-1663