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Autonomously guided parachute delivery systems

Development and test approach

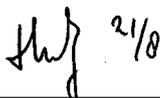
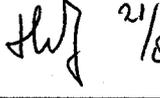
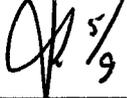
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Abstract

Dutch Space, NLR and Aérazur develop an autonomously guided parachute system for precision delivery of cargo. The system named Spades (Small Parafoil Autonomous Delivery System) and precursors of the system were tested in co-operation with the Royal Netherlands Army and the Royal Netherlands Air Force. The development and test approach applied are presented together with a description of the system and the gained test results.



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1 Introduction

Operations of special forces are sometimes hampered by the limited amount of cargo that a paratrooper can carry under his parafoil. This limitation, together with the identification of other niches in the market for cargo delivery systems, was the reason for starting the development of an autonomously guided parachute delivery system. The basic idea for the development is that in flight the autonomous system behaves identical to the paratrooper for as much as possible. It uses the same type of parafoil and uses a similar flight strategy, giving the largest operational and logistics benefits. The target point, i.e. the place where to deliver the cargo, is entered into the on-board computer of the system before release from the aircraft, or, if operations permit, before aircraft take-off. The development of such a system is a co-operative effort of Dutch Space, NLR and Aérazur. Capabilities of the system are demonstrated by these parties supported by the Royal Netherlands Army and the Royal Netherlands Air Force.

The system was developed and demonstrated by a team of specialists from different companies in different countries. This paper focuses on the strategy applied successfully for the development of the system. A step-by-step approach was followed with gradually more system functionality implemented. An overview of laboratory tests, ground tests, simulations, parachute-deployment tests, remotely controlled flight tests and autonomous flight tests of a demonstrator system is given. Before this overview the Spades system is described. As an example of the good test results the capability of the system to adapt to wind changes during the flight follows the overview.



2 The system

The system (fig. 1) can be subdivided into three main parts:

- the parafoil
- the control-box with on-board computer and
- the payload container.

Commercial-off-the-shelf components are applied in the design as much as possible. The parafoil, a 35 square meter G9-Galaxy of A razur, is a soft pack mounted on top of the control-box. This box, with dimensions 0.45 x 0.45 x 0.40 m (LxWxH), contains the on-board computer, sensors, and the actuators for the control-lines. The payload is fixed to hooks on the corners of the box. Up to now a 160 kg dummy payload is used consisting of a cylindrical bag with easy-to-handle sub-containers, including a bottom with shock-damping material.



Fig. 1 Two integrated test-units ready for flight at Eindhoven airbase

The control-box has two actuators to reel the two control lines of the parafoils in and out such that steering actions defined by a flight control computer can be realised. For the flight control computer an advanced algorithm was developed that was named auto-pilot due to similarities with fixed wing auto-pilot functionality. With the algorithm the system frequently updates the best strategy to reach the target point, based on the relative position of the system with respect to the target point and on the calculated wind vector. Position data are retrieved from a GPS receiver and wind data are calculated by processing sensor data, where the GPS and heading sensors are the prime sources for the data. The sensors and rechargeable batteries for power supply are also in the control-box.

The current system has a radio link between the control-box and a ground station for remote control. In the ground station key parameters reflecting the status of the system are displayed to a remote pilot, who can override steering commands of the flight control computer with control levers for the left and right control lines of the parafoil. For test purposes the current system has additional sensors and a data acquisition and recording system installed in the control box.

3 Step-by-step approach of the development and tests

The tests in the development process had two objectives:

1. In a step-by-step approach gradually larger functional parts of the system were tested. The steps were chosen such that in each step the risks with respect to system loss or damage were minimal and acceptable. The last step in this process showed that the demonstrator system is capable to deliver the cargo within 100 meter from a pre-programmed landing point when the system is released from a C-130 Hercules at 10.000 feet altitude.
2. Flight data in pre-programmed flight-maneuvres was recorded to derive the flight characteristics of the vehicle. These characteristics were needed for the design of the flight control system.

The different tests are described below.

Both single components and the integrated system were tested for as much as feasible in the laboratory. The tests were extended on the ground, but outside the laboratory for the verification of remote control functionality and GPS performance. As VHF radio links for the remote control appeared very sensitive for earth surface disturbances the ground station was installed on an elevated position, the roof of a hangar appeared appropriate for the installation. The ground station had a wide field of view over the surrounding landscape such that a simulated flight on top of a van (see fig. 2) had line-of-sight connection with the ground station over large distances.



Fig. 2 Spades control unit installed on a van for a simulated flight on the earth

The simulated flights on the van demonstrated that the remote control via the radio link, the GPS position determination and display on the ground station, the remote control of actuators and registration of data functioned well. After these tests the control box was considered ready for in-flight tests.

The first flight tests with the parafoil in combination with the payload had been executed in that stage. Before controlled flights with the complete system it was decided to verify that replacing the man under the parafoil by the payload did not influence the parafoil deployment and stability of flight adversely. The parafoil system was dropped at low altitude from a C130 Hercules aircraft of the Royal Netherlands Air Force (RNLAf)(fig. 3). The deployment drop tests (DDT) showed that the deployment and flight characteristics of the combination were good.



Fig. 3 SPADES unit released from the Dutch Hercules C130

Details of the flight characteristics were not obtained from the DDT flights as only data for one setting of control lines per flight was obtained. The development of an auto-pilot algorithm needed more data. Therefore the next flight test phase, the OLDT (Open-loop Drop Tests), applied the system in open-loop control mode, i.e. steering commands were independent of sensor signals. First the pilot in the ground station (fig. 4) tested the system under remote control. In later flights sequential steering commands were programmed in the flight control computer with the remote control option as a backup if the flight profile was not appropriate and for a safe landing. The fixed steering command sequence had the advantage of being well defined compared with manual remote control. Well-defined flight manoeuvres provided better data for the flight characteristic assessment for the auto-pilot development.



Fig. 4 Spades system under remote control from the ground for characterisation-manoevres. The remote control display and control unit are shown in the right section in a laboratory set-up.



The flight tests in the configuration with an active auto-pilot were preceded by computer and hardware-in-the-loop simulations. In a first step the algorithm developed for guiding the parafoil was implemented in a computer simulation environment for the parafoil behaviour as a function of the external parameters (amongst others the wind profiles and parafoil characteristics). The algorithm was verified to guide the parafoil to the pre-programmed landing point in a robust way, i.e. insensitive for wind variations. Different flight strategies implemented in the algorithms were tested to find the best.

In a second step the GPS position, the heading and the steering commands were retrieved from the computer simulations as a function of time for several flights. The GPS position and heading signals were replayed on a PC, such that output of the PC provides data identical to GPS receiver and heading sensor outputs. These electrical signals were fed to the control computer replacing the GPS receiver and heading sensor inputs. The reaction of the control computer as a function of time in terms of steering outputs and flight modes is compared with the simulated reactions. The correlation between computer-simulated data and hardware-in-the-loop simulation results was verified.

After these simulations flight tests with the auto-pilot were executed, where it was always possible to take over control manually via the ground station. At present, with 8 autonomous flights in this Closed-Loop Drop Test (CLDT) phase, it has not been necessary to take over control from the auto-pilot in any of the flights. Airdrop altitudes have been varied between 6.000 feet and 10.000 feet.



4 Test results

Test results guided the development process. Choices of components and design solutions were largely confirmed in tests as good choices fulfilling the requirements. Some aspects, such as the flight control and strategy to approach the target, were improved using test results. During the CLDT phase the auto-pilot has been improved, both the general flight strategy and some assumptions about the earth boundary layer could be optimised. The current landing accuracy is 100 meter or less in autonomous flight, which meets the main goal of the development.

Flight tests are described in some detail below and the capability of the system to adapt to wind changes during the flight without having the wind as an input parameter is addressed as an example of a good test result.

The flight tests have been carried out in the last two years in a wide range of wind-conditions, from 2-6 Beaufort, and at altitudes of 1.000, 4.000, 6.000 and 10.000 ft. In all 18 test-flights, the units have been released from the Hercules C130 in two sequential drops per flight of the aircraft.

The preparation of the test-units was carried out at the Eindhoven airbase, about 200 km away from the drop-zone. Based on general available weather forecast with respect to wind the missions were planned. Later, one hour before the tests, a weather-balloon was used to record a last indication of the wind speed and direction just before the test. This balloon information was only used for the test evaluation.

In the field a landing-point was selected and the co-ordinates were communicated with the airbase. During the pre-flight electronic health-check these data were passed on to the auto-pilot. This is the only information the system needs as an input.

A best guess of the wind-profile is used only for the mission planner to determine the 3-dimensional space-volume where to drop the system. The on-board computer does not need any pre-information on wind. An estimation of the wind-vector is calculated by the auto-pilot/processor during flight.

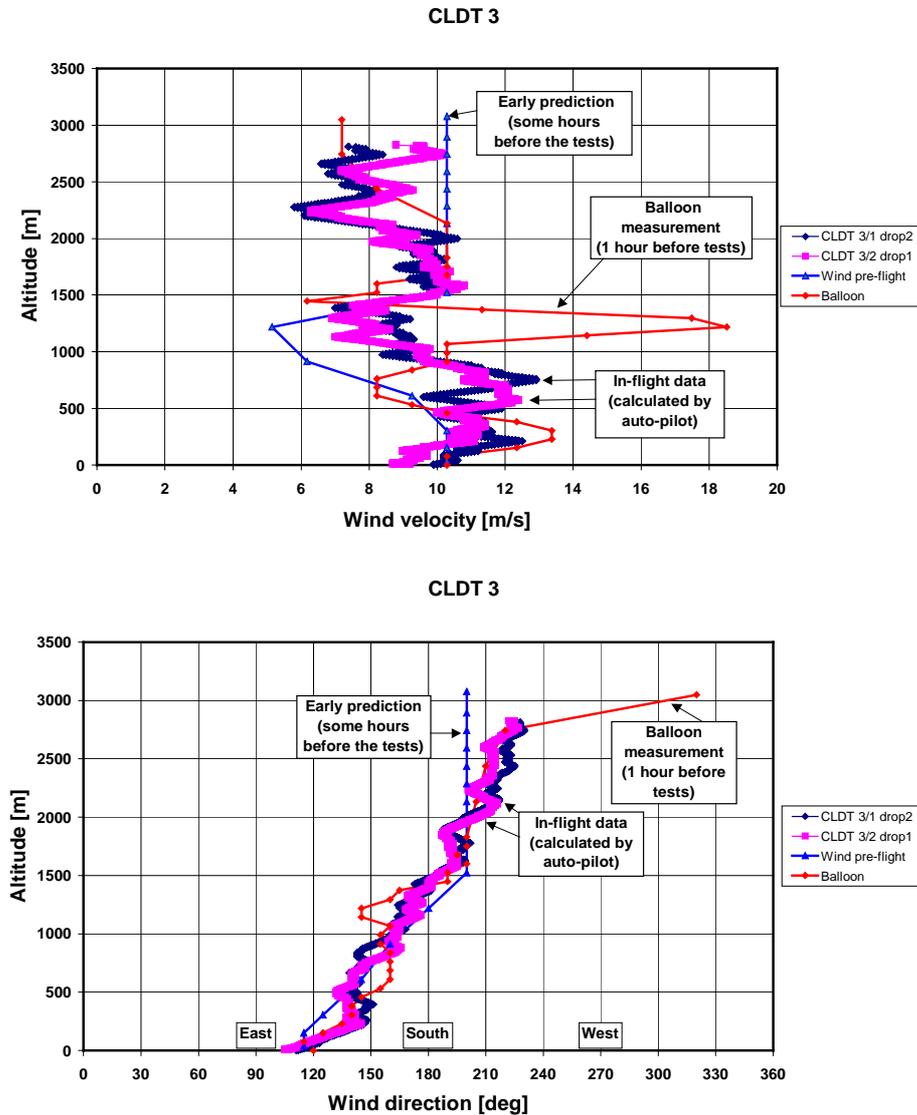


Fig. 5 Wind velocity (top) and wind direction (bottom) measured with weather balloon soundings until just before the flight tests and as determined in the control unit of the two systems for flight planning purposes

As an example, wind-data calculated by the processor in two sequential tests (hence, carried out within one hour on the same day) are shown in figure 5. The calculated wind-velocity and -vector estimated by the auto-pilot during the flight are close to the separately and independently measured data. Only the wind-shear at 1250 m altitude, measured just before the test, is not recognised in the flight-data. This layer could very well be a local phenomenon at that specific instant and/or location. Overall, the estimated values of the wind-data proved to be satisfactory for realising adequate guidance.

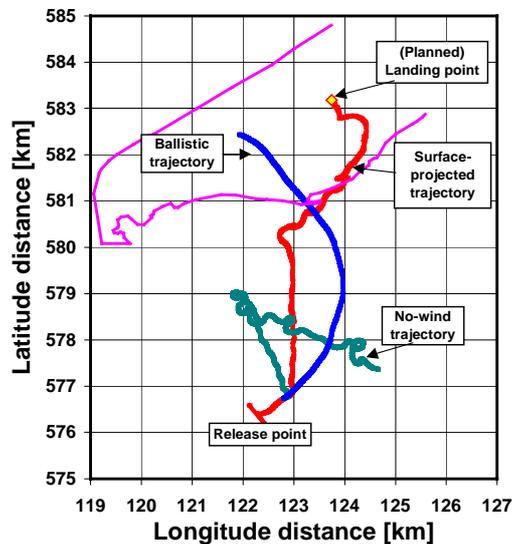


Fig. 6 Ground track (red), ballistic trajectory (blue, the trajectory a ballistic parachute, without horizontal air speed, would have flown) and the displacement of the Spades system due to steering commands of the auto-pilot (green, the trajectory the system with wind effects subtracted). The limits of the test area, the coast line of an island, is shown in purple. A local co-ordinate systems is used with 1 km unit intervals in latitude and longitude.

In the two test-flights the units were released at 10.000 ft (~ 3048m), in combination with a stand-off distance of almost 7 km. The resulting (GPS) inertial-trajectory (projected on the earth-surface) of one of these test-flights is shown in figure 6 (red line). Each square is 1 by 1 km. In the plot the crooked line is the (relative) no-wind line, while the bow-shaped curve indicates the ballistic wind-trajectory (so with wind, but without velocity of the system with respect to the air). The super-positioning of both latter two trajectories results in the trajectory actually flown. In the plot the x-co-ordinate shows the position in East direction in [km], while the y-co-ordinate denotes the position in North direction also on a [km]-scale.

Figure 5 shows that during the descent in the test, the wind-direction rotates from 220° at 10.000 feet (South-West) to 120° (South-East) at the surface. In the ballistic wind-trajectory this rotation-effect is recognised by the curving shape of the trajectory. The no-wind performance of the system is adequately used by the auto-pilot to compensate for this wind-rotation in order to land at the specified landing-location.

This example shows that, although the system does not know the wind-profile in advance, and even if the wind is not 'uniform', the auto-pilot algorithms will react and compensate for it, thus taking care that the unit will land on the right spot.



5 Conclusions

The described development and test strategy with a step-by-step approach was applied successfully and malfunctioning components and software that might have caused problems in flight were identified before flight.

A system was developed thanks to team work of flight operations experts, avionics specialists, software specialists, flight mechanics specialists, mechanical specialists and parafoil specialists from different companies and different countries. Special force paratroopers, the aimed users, are enthusiastic about the handling and the performance of the system.

6 Further development

The initial goal for the development was to work out a demonstrator system that can deliver the extra cargo a paratrooper needs on his mission. The system was realised and after an industrialisation effort it is available for in-service operation. The same system can also be applied for re-supply missions in the field. Apart from systems flying fully autonomously to a target point also remotely controlled systems, controlled by a pilot on the ground can be produced. Optionally the remote control by an in-flight paratrooper might be produced. Furthermore, the technology developed can be applied for systems for heavier payloads using larger parachutes. The larger parachutes may find applications for the military, such as delivering vehicles for special operations, but also for civil applications such as humanitarian aid delivery of food, medicine or water supply equipment.

7 Acknowledgements

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