FASTWing CL flight tests with a high-glide ram-air parachute for 6,000 kg payloads.

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A EU funded cooperation, Autoflug, Cimsa, Dutch Space, National Aerospace Laboratory NLR, DLR, EADS-CESA, CFDn and the Technion University participated in the FASTWing CL project to investigate the application of a 300m^2 high-glide parafoil for payloads up to 6,000 kg. The project acronym FASTWing CL stands for Folding, Adaptive, Steerable Textile Wing Structure for Capital Loads. The ram-air parachute is flight-tested in the project. The deployment is tested with a pilot chute, though the canopy was originally designed for a deployment with a stabilization chute. A dedicated test vehicle was designed and built for the tests to serve as payload and provide fixation for the autonomous guidance unit. The in-flight performance of the flight unit is determined with remote controlled maneuvers during drop tests. This performance was the input for the design of the autopilot algorithms. The flight tests ended with a fully autonomous drop including a successful flare maneuver which was automatically initiated. In this paper the flight experience with the main high-glide ram-air parachute and the flight unit configuration are described, as well as the results of the flight tests.

I. Introduction

A European co-operation of Autoflug, Cimsa, Dutch Space, National Aerospace Laboratory NLR, DLR, CESA, CFDn and the Technion University investigated the application of a 300 m^2 high-glide parafoil for payloads up to 6,000 kg in an EU funded project "Folding, Adaptive, Steerable Textile Wing Structure for Capital Loads" (FASTWing CL). The main objectives are the development of a high-glide parafoil, the development of an autonomous guidance unit (AGU) and to demonstrate the capabilities of this parafoil in combination with the AGU [1].

After the design and production of the parafoil, 12 parachute verification tests are performed and the final flight configuration has been defined which was used during the 9 steerable flight tests. During the first steerable test campaign the control software was updated to optimize the steering of the AGU after which the final 6 flights are performed. The results of these 6 flight tests are discussed in this paper as well as the design of the high-glide parafoil, the verification tests and the final flight configuration. Finally some conclusions are given.

II. High-Glide Ram-air Parachute

In a preceding FASTWing project, a 160 m^2 parafoil with 27 cells was designed and tested for 3,200 kg payload already in 2005. The project was also funded by the EC, within the 5th Framework Program. For the FASTWing CL project the area is extended up to 300 m^2, and the parachute is capable to fly 24 m/s with a total suspended payload weight of 6,000 kg. The extended airfoil planform for the FASTWing CL version is a scaled model of the FASTWing configuration.

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The airfoil of the ram-air parachute was selected by means of an advanced vortex-panel based aerodynamic tool [2] and [3], leading to high aerodynamic and inflation performances. The planform was tapered leading to flexible maneuverability and high gliding characteristics [4]. A scaled model of the parafoil was manufactured and tested in the biggest European wind tunnel at NLR - DNW in the Netherlands. Aerodynamic characteristics of the parafoil were measured for different configurations of the canopy and lines, such as reefing stages, reduced number of lines, turn and brake maneuvers. A wide range of incidence angles of the parafoil was assessed, in order to identify the optimal rigging angle.

The main characteristics of the FASTWing CL parafoil are:

- Area: 300 m^2
- Tapered 0.5 configuration plan form
- 3 de-reefing stages
- Number of cells: 27
- Full wingspan: 35 m
- Aspect ratio: 4.03

The mid-span reefing method was adopted again in the FASTWing CL project, mainly due to the fact that the parafoil deployment and reefing stages are better controllable than using a slider reefing system.

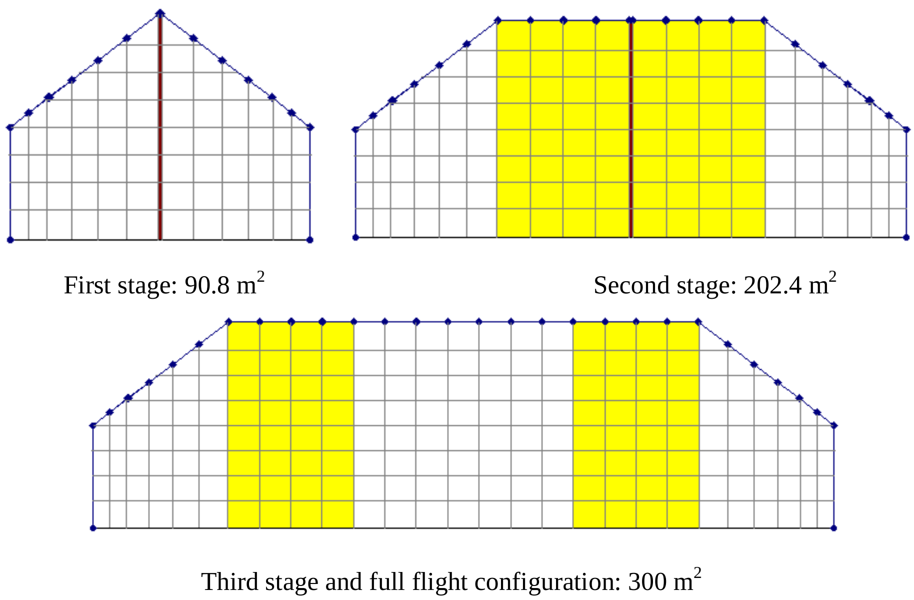

Figure 1: Three different stages of deployment.

During the project design phase parafoil simulations were performed in steady state descent in order to get the maximum tensions values in canopy fabric and lines, leading to the parafoil materials selection. Full flight, turn and brake regimes were assessed for payload weighting up to 6,000 kg as presented in *Figure 2*. The control line deflections are up to 2.5m.

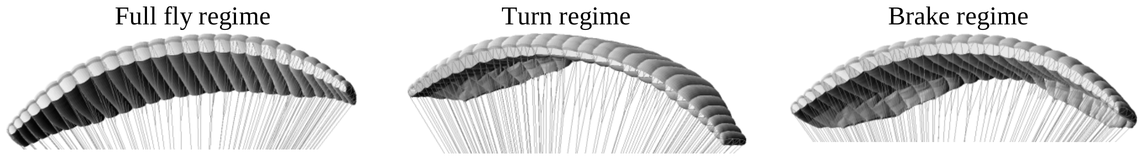

Figure 2: The canopy configuration during different maneuver regimes.

The safety factor was higher than 2 for both, the canopy and lines, leading to withstand strong inflation situations and specially extraction and inflation immediately after the exit of the aircraft by means of a pilot parachute, i.e. at velocities higher than 65 m/s.

III. Parachute Verification Tests and Final Flight Unit Configuration

In the Parachute Verification Test (PVT) series, 12 drops are executed to test the deployment and performance of the complete parafoil system. Initially, a stabilization parachute was planned as an intermediate step in the deployment to stabilize the payload after release, and to decelerate the system down to a maximum velocity of 20 m/s. Although the stabilization parachute flew well after several drop tests, problems with the in-flight separation between the stabilizer and the main canopy forced the project team to replace the stabilizer with a 1.40 meter pilot chute. The opening of the main parachute is then initiated directly after release. Two drops tests with respectively 4,500kg and 5,000kg payloads (composed of A22 drum-units) are performed to demonstrate the opening of the pilot chute and the inflation and de-reefing of the main canopy.

The last 2 drops of the parachute verification are executed using the dedicated test vehicle (see *Figure 4*) but with a dummy AGU and without the deployable nose boom (see *Figure 5*). These two flights with the dummy AGU are performed to verify the behavior of the deployment of the canopy in combination with the super structure in order to minimize the risk of using a fully equipped flight unit with the following flights. The parafoil steering lines are a-symmetrically fixed, so that the system will perform a helix type trajectory instead of an unpredictable long-range gliding trajectory.

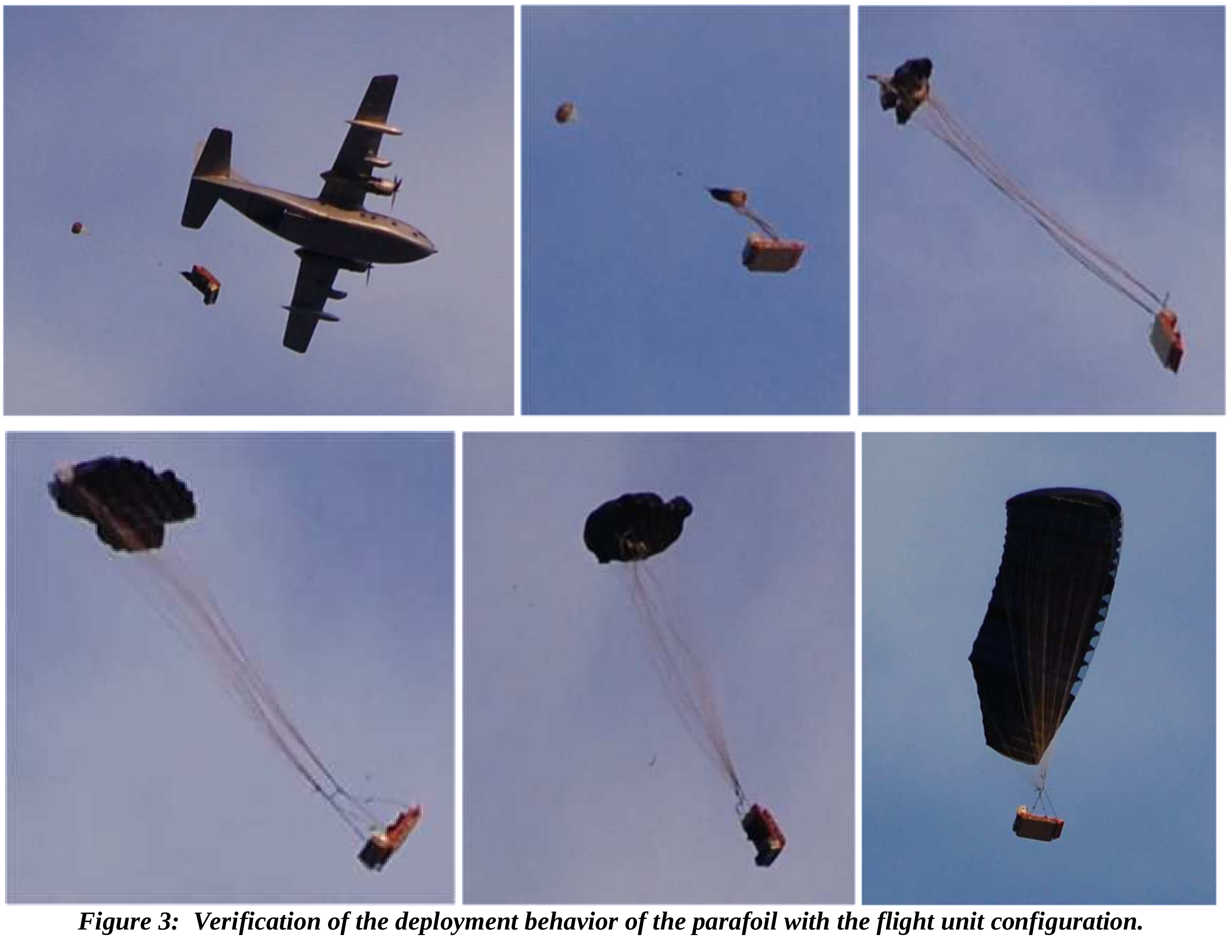

Figure 3: Verification of the deployment behavior of the parafoil with the flight unit configuration.

Figure 3 shows that the flight unit significantly tumbles back and forth so that the risers of the parafoil sweep over the AGU and the front of the flight unit. The experience of these drop tests was used to define the final flight unit configuration (the FDAS was relocated and the deployable nose boom was replaced by a fixed nose boom) and to verify the effective time delays between the different de-reefing stages of the main parachute and the total delay since release for starting the control of the system. The total altitude loss during the deployment and the flight stabilization appeared 1,000m.

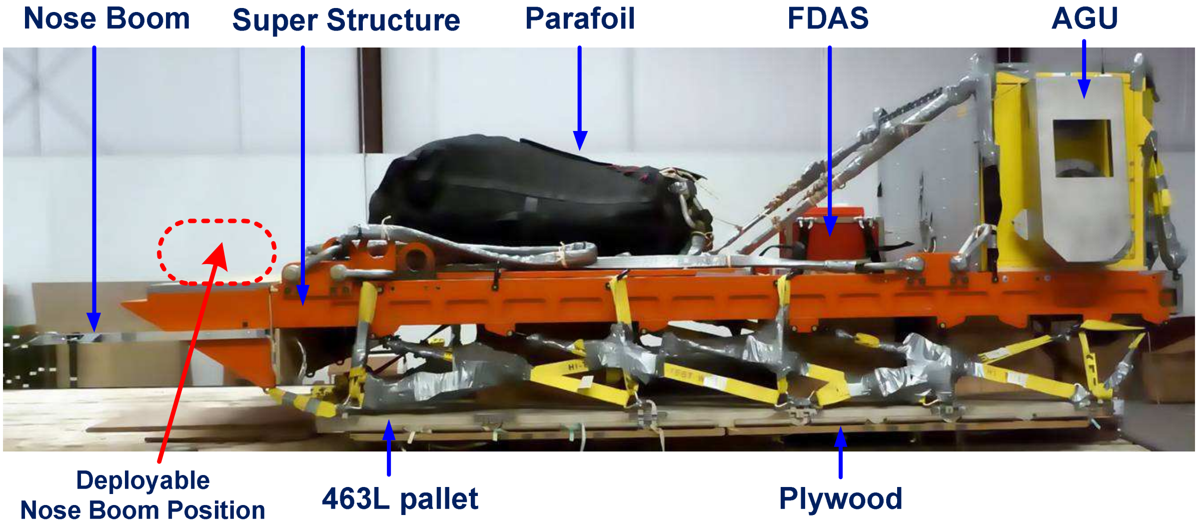

Figure 4: The flight unit configuration.

The flight unit configuration (3,200kg) consists of:

- The AGU
- The structural platform (Super Structure)
- The Parafoil 175 kg
- 463L pallet with plywood underneath
- Paper honeycomb material for damping of the landing shock
- FDAS: Flight Data Acquisition System
- Nose boom with pitot tube and vanes for measuring angle of attack and sideslip.
- Straps and tape, lots of tape

Figure 5: The deployable nose boom.

The superstructure was especially designed to be used for development testing of the parafoil. There was no specific directive to optimize for weight or dimensions. The main configuration restrictions for the flight tests were related to the limitations of the aircraft at the test-facility. The ramp of the aircraft has a maximum load capacity of 3,200 kg which limits the maximum flight configuration mass. The Autonomous Guidance Unit is developed to demonstrate that an AGU can control a 300m^2 parafoil and perform a dynamic flare without being optimized for weight or dimensions as well. It's guidance, navigation and control unit (GNCU) has also a data recording system and it is linked to the FDAS which allows a backup of the collected data. The overall center of gravity of the flight unit is placed as much as possible to the front in order to limit the rotation of the flight unit when it exits the plane.

The results/conclusions from the parachute verification tests are:

- The gravity extraction of the flight unit functions well and rotations are limited
- 4 successful Pilot and Parafoil deployments have been performed
- FDAS should not be placed on top of AGU
- The deployable nose boom can't be placed at the front of the superstructure and has to be omitted
  A fixed nose boom has to be used, which is not optimal and a high risk of failure is expected
- OK to proceed with the Steerable Flight Tests, last two parachute verification tests have shown that it is imperative that verification with a flight representative payload is conducted.

IV. Steerable Flight-test

In total 9 steerable flight tests (SFT) are executed. The first three tests are performed during the first test campaign with the superstructure in which also the last two parachute verification tests are performed. Dropped from 7,000 feet, these flights provided limited data sets due to problems with the steering lines (no break release and entanglement). Although the steering was not optimal, the landings went well, and during SFT #3 a proper flare is applied.

Figure 6: Steerable flight test configuration.

In the final test campaign, 6 flights are performed and an overview of the final test campaign test results is given in Table 1. The parafoil characterization and the autonomous flight verification are discussed in more detail next.

SFT #	Altitude [m]	Flight Duration [sec]	Landing V_vertical [m/s]	Landing V_horizontal [m/s]	Landing Accuracy [m]
4	2558	361	2.16	10.25	474
5	2787	353	2.50	8.77	261
6	3003	411	2.97	13.98	95
7	3030	445	1.41	10.50	222
8	3111	448	3.97	9.66	220
9	3084	366	0.82	11.54	267

Table 1: Final test campaign test results.

Parafoil characterization

The data of all steerable flights are used to determine the aerodynamic characteristics of the system. The characteristic aerodynamic data for the flight unit can be derived from the evaluation of the flight data recorded during pre-defined maneuvers. One of the main objectives of this test series is to determine the in-flight turn-responsiveness of the flight unit with respect to commanded steering line deflections. A sequence of several turn- and brake-(pulling symmetrical steering line deflections) maneuvers are manually commanded by remote control using the radio up-link via the ground station. In the turn maneuver one steering line is deflected while the other is kept at zero deflection. In a brake maneuver both steering lines are both pulled down to the same deflection.

The characterization maneuvers are performed by overruling the autopilot homing-commands during the (regular) descent phase when the main canopy is fully deployed. The final landing accuracy is not an objective in these flights, since the main objective of the characterization drops is to determine flight characteristics of the vehicle in-air. It is even more important to finish initiated maneuvers than to perform an accurate landing. Only when the preliminary design of the autopilot algorithms is already sufficiently stable the landing phase can be performed automatically. In that case a first estimation of the control settings for the flare can already be gained from the flight data. In every next drop the initial control setting is updated and refined.

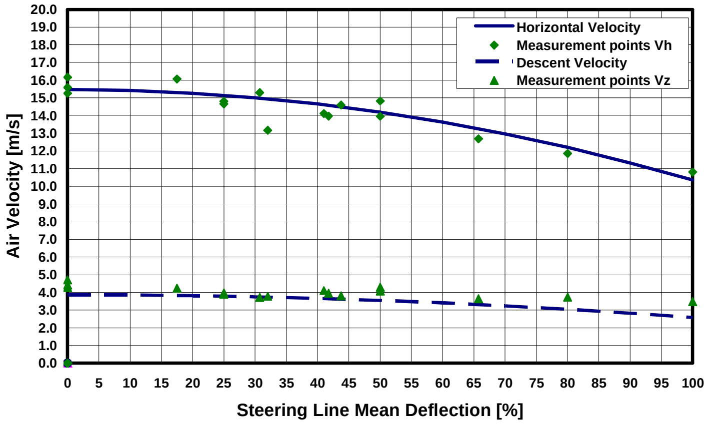

Figure 7: The horizontal and descent system velocity as function of deflection.

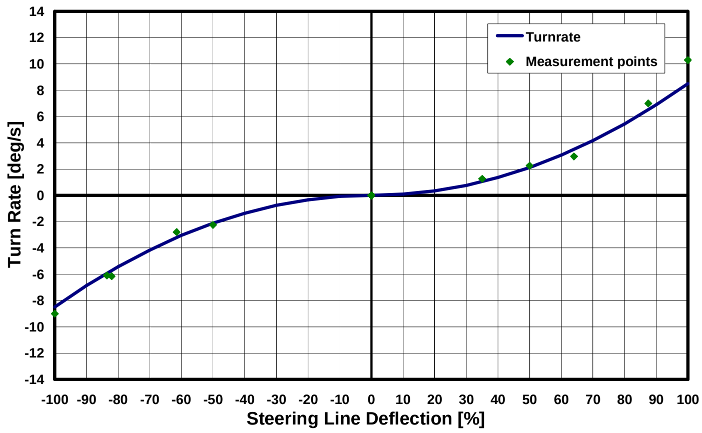

Figure 8: The turn rate as function of deflection.

The system air velocity in [m/s] as function of the deflection [% full stroke deflection] is presented in Figure 7. The solid upper curve is the horizontal velocity and the dotted lower curve is the vertical descend velocity. The measured values are indicated by the symbols, and the values are derived from the flight data recorded during the execution of the maneuvers. The curves are the approximations of the measured values. It shows that the stationary system velocity reduces from 15.5 m/s down to 10.3 m/s. when the steering lines are pulled down from 0% up to 100% brake deflection. The stationary descent velocity reduces from 3.9 m/s down to 2.6 m/s.

The turn rate of the system in [deg/s] as function of the deflection [% full stroke deflection] is presented in Figure 8. The measured values are indicated by the symbols, also in this figure, and the values are derived from the flight data recorded during the execution of the maneuvers. The curves are the approximations of the measured values. The turn rate is between 8 and 10 deg per second at maximum deflection of 100%.

The full flight system velocities for a payload of 3,025 kg can be derived from the values presented in Figure 7 by using the values at zero-deflection. The full flight horizontal velocity is 15.5 m/s and the full flight descent velocity is 3.9 m/s. The in-flight effective glide ratio for the system is then 4.0, being the ratio between horizontal and vertical velocity. Note that the effective glide ratio is less than the theoretical glide ratio of the canopy alone, because of the additional drag of the payload.

Autonomous control verification

The last 3 flight tests are performed autonomously after update of the autopilot algorithms (note SFT # 8 was semi-autonomous, it did include some additional manual maneuvers to collect steering data). The update is based on the aerodynamic characteristics derived from the evaluation of the recorded flight data during the specified maneuvers in the previous 6 tests. The system is now programmed to find its way to the target autonomously. The guidance of the auto pilot becomes active after full completion of the release events: the system release, the parafoil deployment and the short acquisition period. A flare is executed at the end of the flight during the landing phase. In the autonomous flights the autopilot algorithms are tested in-flight to verify the performance with respect to the behavior and the precision landing accuracy of the flight-vehicle. Several autonomous flights are required to fine tune the different control-parameters, like the initiation timing of the flare at the end of the flight. Also variation of the payload mass is required for this. Clearly 3 flights are not sufficient to fully optimize the autopilot algorithms.

The last flight is a fully autonomous flight performed with a 3,025 kg payload and dropped at 3 km altitude with 3.1 km stand off distance. The trajectory projection of this flight is shown in Figure 9. The actual trajectory is displayed in relation to the mission planning used for the definition of the flight. Several safety circles are still visible in the same display. The flight trajectory is indicated by the black solid track. The target is marked with the yellow dot at the bottom of the trajectory and the release point is shown at the upper part. The grid is 1km x 1km.

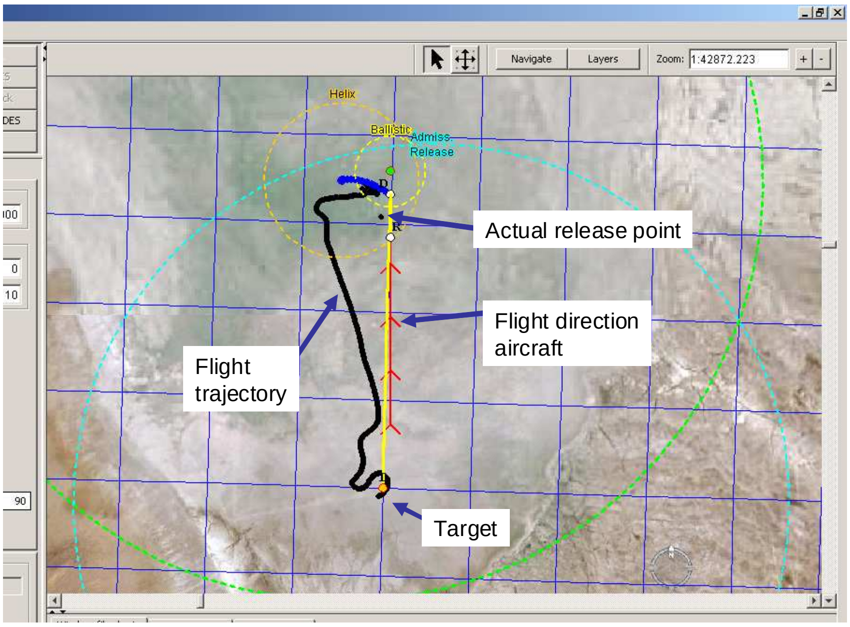

Figure 9: Trajectory path of the autonomous flight after release at 3 km altitude.

The final landing accuracy in the flight is 267 m. The landing accuracies in the other autonomous and semi autonomous flights are 222 m and 220 m. In the semi autonomous flight the landing approach and landing are performed automatically. So the landing accuracy of 267 m of the final flight is not a single shot value. Nevertheless, in the future flight parameters can be more optimized to obtain an even better accuracy.

A flare maneuver was performed at the end of the flight. The vertical landing velocity was reduced from 3.7 m/s to 0.82 m/s at touch down. The full flight forward velocity was reduced from 15.5 m/s to 11.5 m/s. The reduction in vertical velocity was obtained with perfect timing of the flare. This timing was triggered by the altitude sensor which was set at an initialization time of 14 m altitude above the landing surface. The radio altimeter was instrumented by The National Aerospace Laboratory NLR.

Figure 10: Soft touch down by right timing of flare maneuver at landing.

V. Conclusions

During the FASTWing CL project several parachute verification tests and steerable flights test are performed, resulting in a final fully autonomous flight with direct opening via a pilot chute of the 300 m^2 high glide ram-air parachute for precision airdrop with payloads up to 6,000 kg. Due to the maximum allowable load of the ramp of the available aircraft, the parafoil is flight tested with a 3,025 kg suspended mass.

The effective glide ratio of the parafoil in combination with a payload is found to be in the order of 4.0. The aerodynamic performance of the system is derived by determining the forward and descent speeds as function of the deflection from pre-defined turn and brake maneuvers. The full flight forward speed at zero steering line deflection was 15.5 m/s and the vertical speed 3.9 m/s for the 3,025 kg suspended load.

The landing accuracy in the autonomous flight is 265 m, which is in the same order (220 m) as in the semi-autonomous flights with only an automatic landing approach and landing. The flare maneuver reduced the vertical speed from 3.7 m/s to 0.82 m/s, which resulted in a soft landing.

Several flight parameters for increasing the landing accuracy could not be optimized further during the program due to the limitation of the amount of drops. Also the increase of the payload range can be an extension of the parafoil application.

The two parachute verification drops have shown that the verification with a flight representative payload was imperative to identify the behavior of the risers of the parafoil during deployment.

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