AUTONOMOUS TAKE OFF AND LANDING OF THE *SHARC* TECHNOLOGY DEMONSTRATOR

Simone Duranti
Saab Aerosystems

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Abstract

SAAB is currently working on several UAV demonstrator projects and has recently flight tested a subscale Unmanned Combat Aerial Vehicle demonstrator called SHARC, conducing for the first time fully autonomous missions, including Autonomous Take Off and Landing (ATOL). The ATOL functions are herein described in detail.

The main objectives of the SHARC project are to demonstrate advanced autonomy on unmanned aircraft, the capability of driving smaller and quicker development processes and to test the airworthiness process involving the Military Flight Safety Inspectorate of the Swedish Armed Forces.

Simulator and Hardware-In-the-Loop test sessions paved the way to flight testing. The importance of reliable simulation models has been once more highlighted. Ground roll dynamics and ground effect aerodynamic models had been ad-hoc refined in order to predict the behaviour of the aircraft during the critical phases of rotation and touch down.

In preparation to the flight test campaign, ground rolls have for the first time been performed at the Saab's flight test centre in Linköping. The flight test campaign has been fully successful. The autonomous landing functionality is operationally invaluable, since it lowers the risks embedded in manual remote piloting during high-gain tasks.

1 Nomenclature

ATOL	Autonomous Take-Off and Landing
BVR	Beyond Visual Range
COTS	Commercial Off-The-Shelf
FCS	Flight Control System
FLYGI	Swedish Military Flight Safety Inspectorate
FTI	Flight Test Instrumentation
FUT	Swedish Military Flight Test Permit
GCS	Ground Control Station
GSE	Ground Support Equipment
HILS	Hardware In the Loop Simulations
MAR	Miniature Radar Altimeter
RTB	Return To Base
SHARC	Swedish Highly Advanced Research Configuration

2 Background

2.1 SHARC and FILUR

Since the late 90-ies SAAB had been carrying out preliminary studies about several Unmanned Aerial Vehicles (UAV) concepts but not taking them into flying demonstrators. In 2001 it was decided to start the SHARC Technology Demonstrator project: a small dedicated team was given the task to develop, manufacture and flight test an UAV system including an avionic system and a Ground Control Station (GCS) that could be re-used later in a second demonstrator, to be later developed, called FILUR (see Fig. 1).

Because of a limited budget and good in-house experiences from flight tests of instrumented sub-scale aircraft, it was decided that the SHARC Technology Demonstrator should be in 1:4 scale of the original SHARC design. One of the major goals of the project was to test the airworthiness process for a military UAV, and this could well be achieved even with sub scaled aircraft. Even the goal of testing a lean development process for demonstrators could be achieved in that way.

The SHARC project was initiated in 2001 with first flight less than one year later, on

Fig. 0 – SHARC (left) and FILUR (right) with a *JAS39 Gripen* on the background

February 11th 2002, with the basic version. The more advanced version made its maiden flight on April 9th 2003, less than two years after project start. In September 2003 the SHARC flew a number of missions beyond visual range, ranging around 20 km from the GCS. In January 2004 the effort towards the development of the ATOL functionalities was initiated, and led to a successful flight test campaign in August 2004, during which fully autonomous mission were demonstrated, from standstill to standstill.

Early in the project it was decided that SHARC should be operated on a Swedish Military Flight Test Permit (FUT), just like any other Swedish military test aircraft, in order to provide experience from the airworthiness process for an UAV. Application for FUT in Sweden is based on an Airworthiness Declaration and means that the UAV system should be:

- Correctly designed according to a Product Development process with designated design reviewers;
- Design should meet well defined Airworthiness Standards, approved by FLYGI;
- Manufacturing according to processes with quality assurance and inspections;
- Correctly maintained according to specific publications (Maintenance Plan and Maintenance Instructions) by certified technicians;
- Correctly operated according to specific publications (Flight Manual and

Maintenance instructions) by certified pilots and technicians, and in compliance with approved ground and flight test plans.

FLYGI was involved early in the project and agreed to refer to an Airworthiness Standard from Australian CASA, based on FAR 23, as a base for the FUT. FLYGI followed up the project closely from early design to completed flight test campaigns.

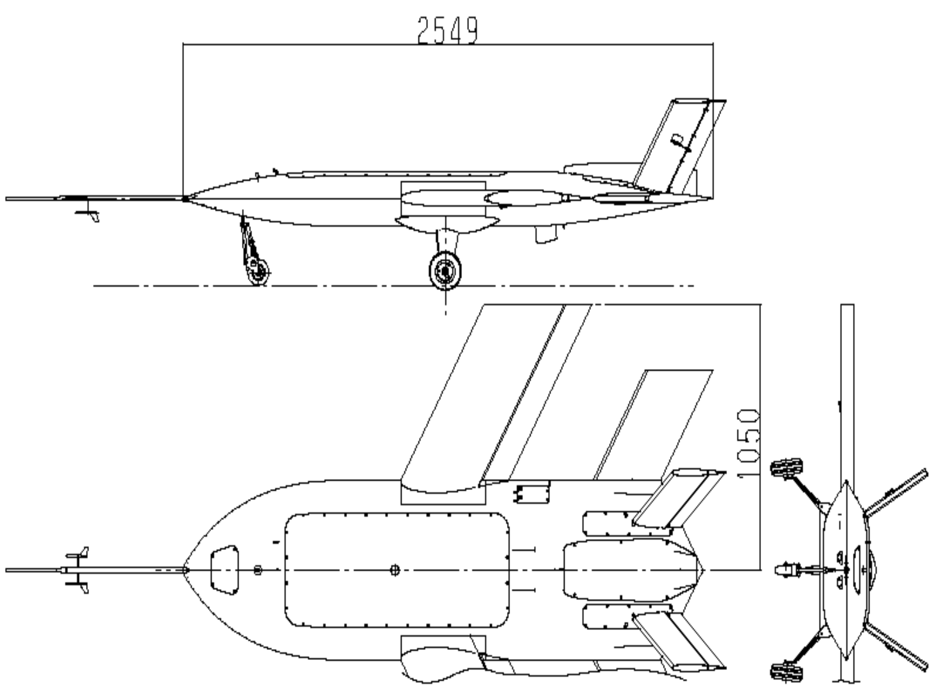
2.2 The SHARC platform

The SHARC system is composed by two flying demonstrators, a GCS and some GSE for engine start and cooling air supply on ground. A basic version of the flying platform is even available in two Trainer Models, used for early aerodynamic and flying qualities evaluations, and still in service for pilot training.

The SHARC (Fig. 2) is a 60 kg jet-engine driven aircraft. A fixed robust tricycle landing gear has been chosen taking into account the tests of autonomous take-off and landing (direct landing without flare); COTS components have been used as much as possible (engine, servos, valves, many sensors, etc.). The airframe, manufactured in light-weight composite materials, weighs only 8 kg (without landing gear).

The payload consists of a forward looking colour video camera, with a video down-link.

The avionic system (hardware and software) is designed and manufactured by SAAB and is based on the Flight Test Instrumentation system COMET 15, used in the *Gripen* and *Viggen* fighter aircraft. Before the decision to develop an in house avionic system,



Wingspan :	2.1 m	Fuel :	JP-8 (MC75)
Length :	2.5 m	Endurance :	≈ 40 min
Speed range :	80-320 km/h	Altitude :	< 2000 m
MTOW :	60 kg	Range :	≈ 30 km
Engine (Turbojet) :	AMT Olympus		

Fig. 2 – Specifications of the SHARC

a market survey was conduced, but no existing system was fulfilling specifications. Electro-optic fibres, or “fly-by-light”, are used to the actuators in order to minimize the risk for electro magnetic interferences. SHARC has a complete FTI with a SAAB designed and manufactured nose-boom.

Many software functions are re-implementations of existing algorithms previously developed for other SAAB aircraft: the waypoint navigation algorithm comes from the *AJ 37Attack-Viggen* and AHRS from *JA37 Fighter-Viggen* and *JAS 39 Gripen*.

2.3 Operating modes

The aircraft can be operated both in manual and in autonomous mode. In autonomous mode the aircraft flies a route of pre-programmed waypoints, including autonomous take-off and landing if so is wished.

When flying autonomously, no control-link with the GCS is virtually needed to fly, but it is of course required to be able to terminate the flight in emergency cases. Therefore some functions have been built-in to detect and react to control-link losses. If loss of control link is detected, the aircraft enters automatically the so-called Return To Base (RTB) mode, i.e. it heads to the GCS, trying to restoring the link by decreasing the distance from the transmitting antenna. Even the RTB routes can be pre-programmed, so that no-fly zones can be avoided even during this phase. If the control link is not restored after a predefined amount of time, the aircraft enters the “termination” mode, i.e. it heads to the closest assigned termination area, where it shuts down the engine and initiates a controlled descending spiral. A detailed explanation of the available flight modes is available in [1].

In manual mode the pilot operates the aircraft by a control-box, which is connected to the GCS by a 100 m long cable, so that the pilot can have direct visual contact with the aircraft during take off and landing. Manual flight BVR is possible thanks to a pair of video-glasses where the on-board camera view can be presented. In case of video link failure, a virtual reality presentation of the aircraft can be supplied to the pilot, animated by the incoming telemetry data. A Head Up Display presentation has been developed, being able to present overlaid video and flight parameters (Fig. 7).

Antennas for up-link (control) and down-link (telemetry) are omni directional, while the video antenna, which was initially omni directional too, has been replaced by a set of directional antennas.

2.4 Why Autonomous T/O and Landing?

A large variety of take off and landing techniques have been historically employed by UAV designers all over the world. Many of them have been very unsuccessful, exposing the vehicles to considerable risks. Today’s unmanned aircraft still report poor reliability statistics, about one third of the accidents occurring during the take-off and landing phases (operational procedures and technical failures equally sharing the remaining two thirds [2]).

During the initial attempts to develop UAVs, the tendency was to simply move the pilot from the cockpit to the ground, by inserting a remote control mechanism, without changing the operational procedures: the pilots were still controlling directly the control surfaces, through sticks and pedals in a cockpit on ground, in the best cases aided by some kind of FCS. An inherent vulnerability was thus built into the systems, the safety of which was completely hanging on the reliability of the communication links. In modern UAVs high level automation, or autonomy, is an unspoken requirement. By automating the take-off and landing phases the impact of human factors can be sensibly reduced, thus raising the total safety level and reducing the workload of the operator.

These concepts were confirmed by the initial experience collected during the first two flight test campaigns with the SHARC. Take off and landings had been performed manually, with the pilot standing on the side of the runway holding the remote control box in his hands. Major problems had been reported during the initial attempts, mostly due to poor cue of the lateral position of the aircraft relative to the runway centreline, and to an instinctual tendency of the pilot to slow down the approaching aircraft, ending up on the backside of the drag curve when attempting the flare (see [1] for more details). Only after several attempts, and a very careful definition of the landing procedure (including the introduction of a "decision heights" and observers on the ground aiding the pilot in assessing the lateral position of the aircraft during the final descent) flawless landings became a routine issue. Anyway, the pilot does still now define the manual landing procedure as "very unpleasant". In Fig. 3 a statistics of a sample of the landings performed during the first two test campaigns is reported; the spread of the outcomes highlights the impact of the human factor.

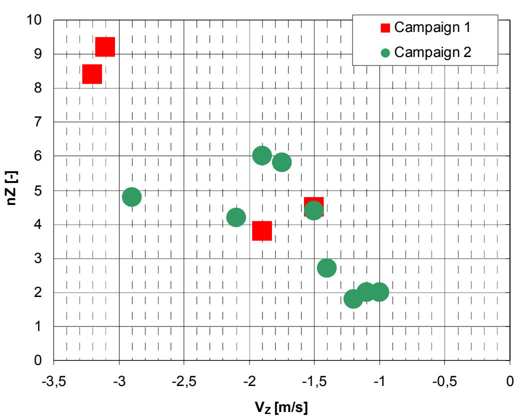


Fig. 3 – Load factors at touch down

Strengthened by these experiences, the ATOL system for the SHARC was specified according to the following guidelines:

- The system should be *fully autonomous*, designed for hands-off operation, i.e. relegating the pilot to a monitoring function; in particular there should be a clear distinction between the manual mode (pilot-in-command) and the autonomous mode (autonomy-in-command);
- The system should be self-contained, without landing aids of any sort on ground.

3 Design choices and challenges

3.1 General

The major challenge for the automation of precision tasks like take-off and landing is the *localization* problem, i.e. to know with high accuracy and robustly the UAV position relative to the runway, during the airborne phase as well as during the ground phase, both in elevation and sideways.

Differential GPS (DGPS) was a natural choice; since selective availability has been removed (May 2000) the accuracy is fully satisfactory for precision landings, at least sideways. Blending with the onboard Attitude and Heading Reference System (AHRS) gave the needed robustness, and a certain resistance to drift in case of GPS fall-out.

It has to be highlighted here that a number of issues must be considered before employing the GPS as only localization mean for operational systems, in particular: a) a weak point of the use of GPS is that the satellites are so far controlled by only one nation, which makes the opportunity to use it as ordinary localization source a political question: a military system that localizes uniquely by GPS can fail exactly when its use is more needed. With this as background, the Swedish Armed Forced have issued a directive stating that military navigation system must not rely uniquely on technologies that Sweden does not have full control on. This doesn't automatically mean that GPS can not be employed, but that there must be alternative sources as back-up; b) another weak point of the GPS signal is its weak resistance to jamming and interference: the area around an airport can be easily jammed with a 1 Watt, hand portable scrambler, the assembling instructions of which can be found on the internet. Moreover, if the jamming action is intermittent, it's even virtually impossible to localize its source (both issues have limited relevance for a technology demonstrator as the SHARC).

For localization on the vertical channel, GPS is less accurate (typically by a factor 3 compared with accuracy on the horizontal

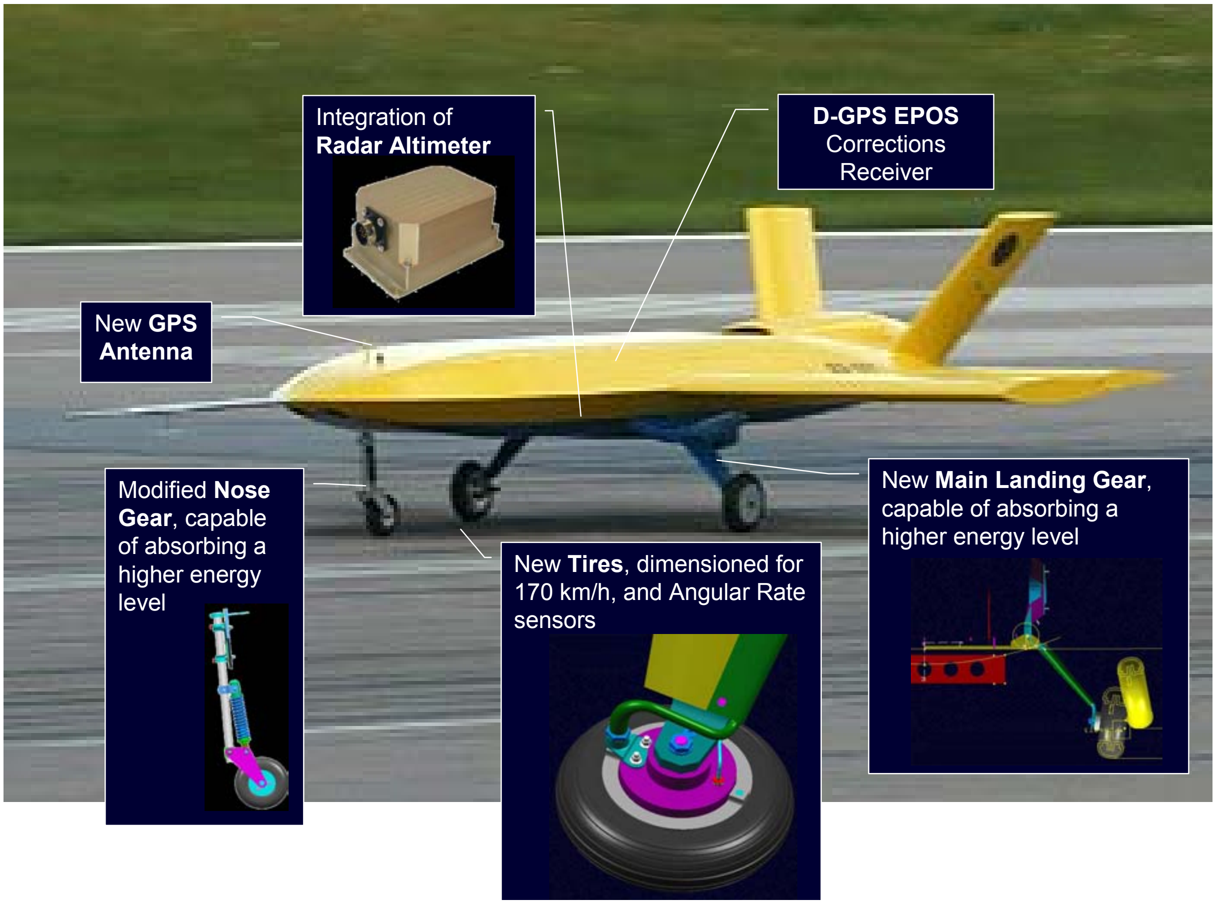


Fig. 4 – Modifications on the platform introduced for the ATOL effort

plane). To accurately estimate the altitude relative to the runway is critical for the precision of landings. Even if a direct landing technique is employed (i.e. without flare), the altitude uncertainty causes an uncertainty of the touch down location with a ratio of about 1:20 (10 m uncertainty in altitude gives 200 m uncertainty along the runway direction).

To cope with the requirement on the accuracy for the altitude measurement it was chosen to integrate into the avionics system a Miniature Radar Altimeter (Mk V from *Roke Manor*), in order to be able to automatically recalibrate the barometric altitude right before landing.

3.2 Autonomous Take Off

To lift a UAV from the ground with a conventional take-off is relatively difficult compared with other techniques (catapult, etc.). The difficulties lie mostly in holding a good directional stability during the ground acceleration, including the rotation phase: the FCS has to smoothly shift from a “ground mode”, where directional stability is mainly obtained by acting on the nose wheel, to an “airborne mode”, where the heading is controlled by the rudder.

The autonomous take off procedure has been designed as follows:

1. The operator lines up the aircraft in proximity of the runway's centerline, in manual mode;
2. After having obtained the take-off clearance from the tower and the green light from the test conductor, the operator selects "AUTO" mode;
3. Brakes' release, acceleration, rotation, and climb occur fully autonomously, until connection to a pre-programmed navigation route at 50 m altitude; during the whole sequence the aircraft navigates guided by an algorithm which minimizes the lateral offset from the runway's centerline.

The operator can abort the autonomous take-off at any time, until rotation is initiated, by triggering a contingency mode that makes the aircraft braking until standstill: this function has shown to be invaluable to gradually test the autonomous ground roll capability. When rotation is initiated the take-off can not be aborted anymore (of course the operator can always take over to manual control, or trigger the emergency termination at any time).

In case of control link loss the same logic applies: the aircraft brakes autonomously if the failure occurs before rotation is started, and otherwise neglects the failure until connection to the navigation route, switching to RTB mode only then.

3.3 Autonomous Landing

The autonomous landing procedure has been designed as follows:

1. A precision flight path following mode is engaged around 2 km before the appointed touch down point (at 150 m altitude): in this mode the aircraft tracks a descending path (γ -4°), aligned with the runways' centerline;
2. At 30 m altitude the flight path is changed in order to keep a gliding angle of -2°;
3. At 4 m altitude, the FCS switches to a "vertical speed mode", holding a constant vertical speed of -1.2 m/s, until touch down; no flare is attempted;
4. Touch Down is detected by angular speed sensors mounted on the wheels of the main landing gear; when the "on ground" condition is obtained the engine is set to idle, and the braking phase initiated, until standstill.

At 30 m an autonomous decision altitude has been defined: in case of control link loss below 30 m the landing is simply continued, until standstill. If the loss occurs above 30 m the landing procedure is aborted, and the standard RTB sequence is initiated instead.

4 Hardware in the Loop Simulations

The HIL simulator (already developed for the preparations before the maiden flight in 2003) consisted of one of the SHARC platforms coupled to a SUN workstation (Fig. 5). All aircraft sensors were disconnected and replaced by digital inputs generated by the simulation SUN workstation. The inputs to the workstation were the positions of the control surfaces of the aircraft, measured by potentiometers. In that way all avionics (except the sensors) could be tested in a very realistic environment, where latencies, servo dynamics, surface free-plays, wirings and all interfaces were "real".

The sensor properties were simulated: the simulation models included sensor noise properties, beside all typical blocks composing a flight simulator (aerodynamics, engine performance, landing gear, atmospheric and turbulence data). The facility included the possibility of simulating a number of failures, such as engine flame-out, sensor failure, GPS failures, etc. Control link failures could be reproduced, being the GCS was part of the hardware in the loop (it was sufficient to unplug the transmitter's power supply).

In preparation for the ATOL test campaign, a number of features have been added to the simulator, in order to reproduce a more realistic environment particularly focused on the critical phases of take-off and landing:

- A ground effect model has been added, after an accurate aerodynamic analysis of the available take-off and landing data collected during the first two campaigns. The analysis showed that ground effect was clearly noticeable during take-off (thus affecting the rotation phase), while it was negligible during landing;
- The stiffness of the main landing gear has been accurately modelled, in order to be able to predict the tendency of bumping at touch down.

5 Ground and flight tests

Flight tests took place at the NEAT/Vidsel test range in northern Sweden [3], in restricted and controlled airspace, and with almost un-populated ground.

The flight test program had been organized in the following order:

- High speed rolls (manual and autonomous), at ground speeds up to 120 km/h; the gains of the yaw control loops have been fine-tuned during this phase;
- Manual check-out flights for general testing;
- Autonomous Take Off (nominal procedure);
- Manual Landing patterns to collect data from the installed MRA: the results showed that the *ad-hoc* developed filtering algorithms functioned as intended, and compensated for the known deficiencies of the sensor;
- Autonomous Landing "on the cloud": the complete autonomous landing sequence was tested, with a 30 m altitude offset on the nominal flight path; the test was considered completed when the nominal touch down point (at 30 m

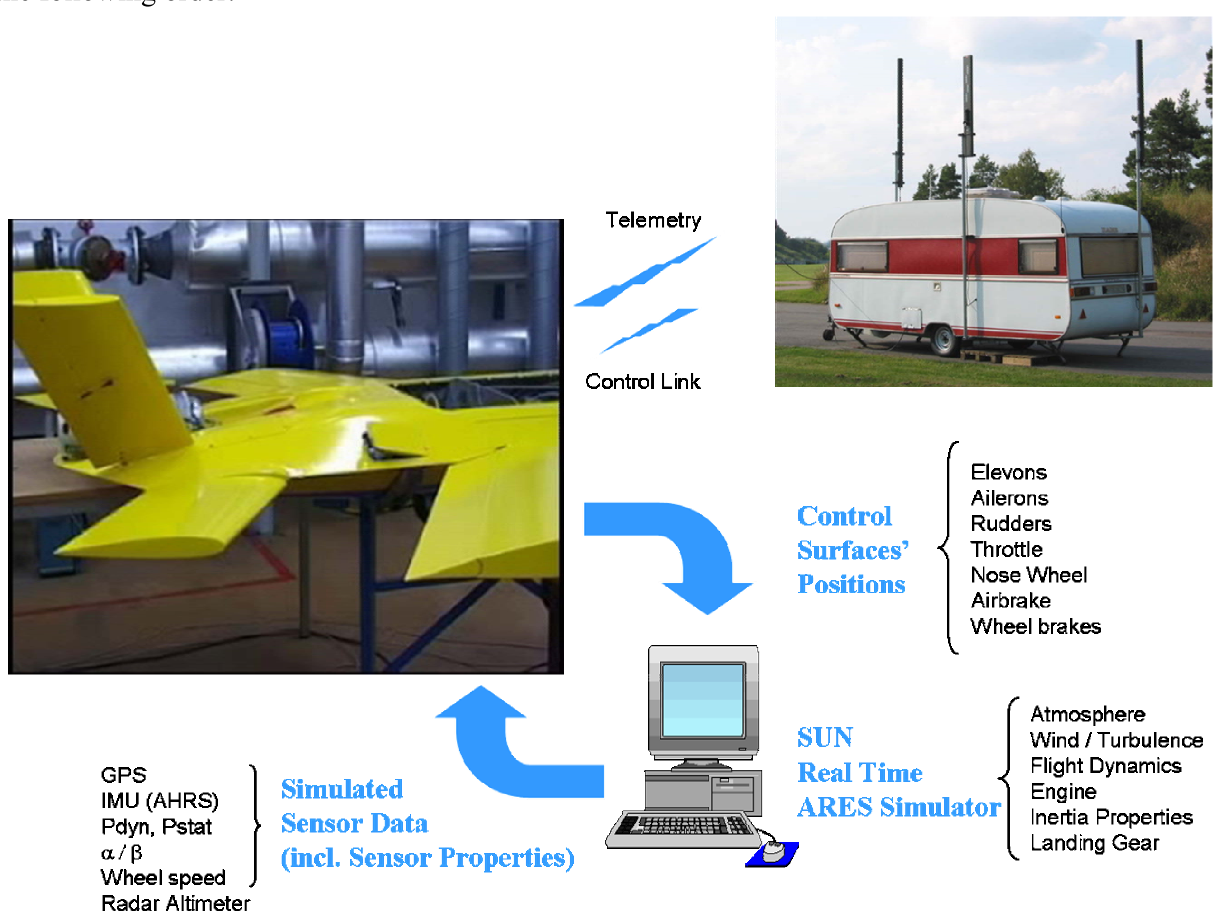


Fig. 5 – Setup of the Hardware in the Loop Simulator

altitude) was passed: the pilot could then take over the manual control of the aircraft and perform a manual landing;

- Autonomous Landing (nominal procedure), with a decision altitude at 30 m, where the test conductor was supposed to make a Go-No Go call for the continuation of the landing, based on the current state of the aircraft relatively to the nominal landing path; an ad-hoc presentation of the flight path, overlaid on the nominal path with acceptable tolerance levels has been developed in the telemetry presentation program and supplied to the test conductor;
- Complete autonomous missions, including autonomous take-off, navigation and landing.

Some minor problems have been highlighted, without requiring any immediate action:

- Less-then-optimal directional control on ground at high speed and during rotation: the problem is mainly due to the fact that rudders and nose wheel obey to a common steering channel, which prevents independent control and optimal gain-tuning for both the ground and the airborne phase;
- The performance of the Miniature Radar Altimeter was worse than expected, but still good enough for precision landings on concrete runways;
- The EPOS differential GPS correction has never been available on ground, at RFN. The signal has been obtained first when the aircraft was already in the air or on a support on ground that lifted it off the ground around 1 meter. This means that no DGPS could be available for autonomous takeoff.
- A tedious problem that has been encountered is that the magnetic compass showed to be very sensitive to

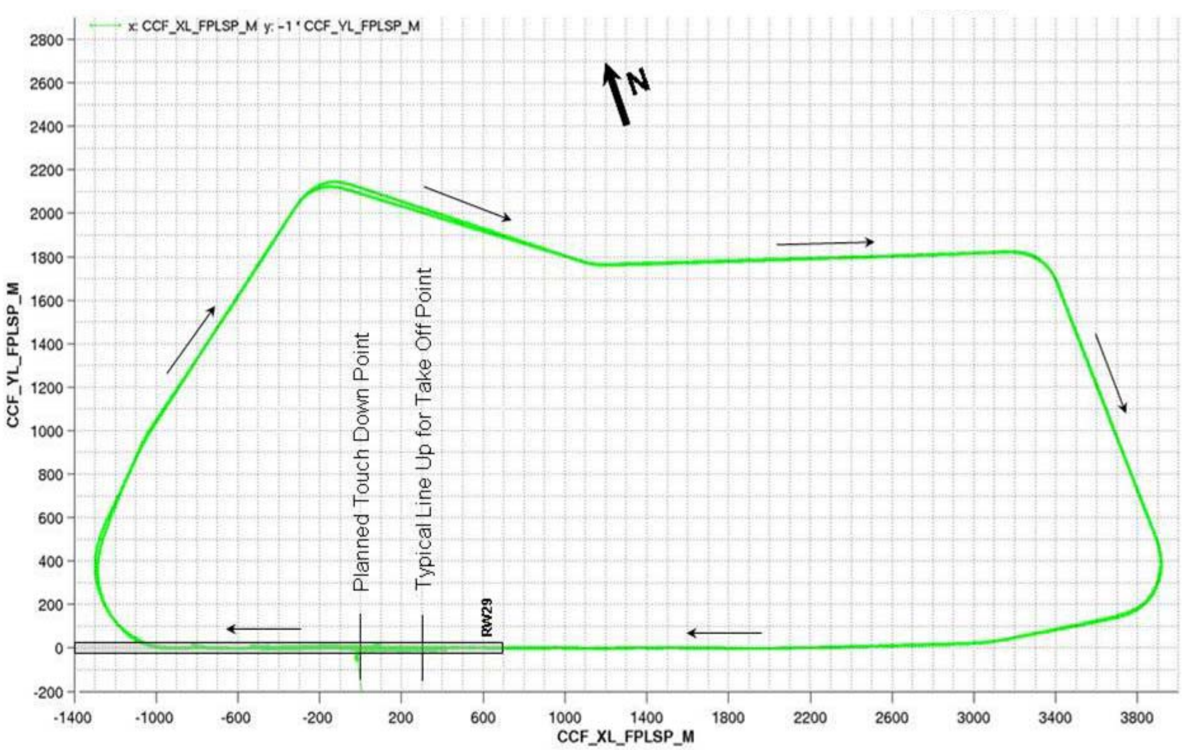


Fig. 6 - Ground track recorded during a mission that was run twice, showing the almost perfect overlay of the flight paths (longitude and latitude in meters on the X- and Y- axis)

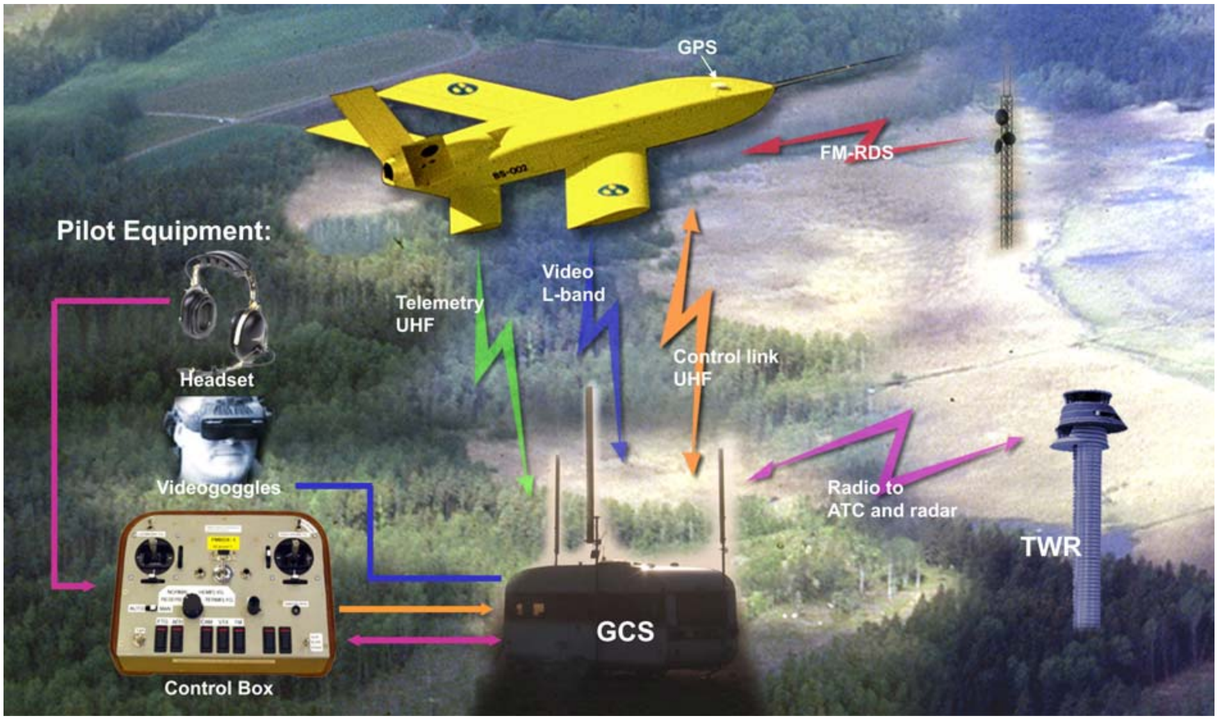


Fig. 7 – Overall view of the communication and control system

local magnetic fields induced by the iron bars below the runway surface. Due to the SHARC dimensions and configuration, the compass is located about 35 cm above the runway surface. Below a given velocity, no information about the heading is available from the GPS, and the magnetic compass is the primary source for heading measurement.

Besides these minor glitches, the test campaign has been very successful, and carried out without significant problems. A number of fully autonomous missions have been completed, in several wind conditions, during which the ATOL functions showed a repeatable and robust behavior. In fig. 6 the ground track recorded during a fully autonomous mission is reported; in particular the track refers to a mission that was run twice, i.e. taking off autonomously right after having landed autonomously: the flight paths do almost coincide.

6 References

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