MINIATURIZED AND LOW-COST OBSTACLE WARNING SYSTEM

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Abstract

This paper reports on a novel development of a miniaturized and low-cost near field obstacle warning system for helicopters based on an adapted electronically steerable, automotive radar. This system is intended to be used as a flight aid to enhance situational awareness and flight safety by detecting and informing the pilot about obstacles in the near vicinity of the helicopter. The activities described herein are performed in the frame of a research project partially funded by the German Federal Ministry of Economics and Technology (BMWi). Between January 2010 and March 2012 the system concept was elaborated and a first prototype of the sensor system was developed and successfully tested both in ground and flight tests. This paper will describe the system concept, its design considerations and it will present first test results.

1. INTRODUCTION

The helicopter's unique hover and vertical take-off/landing capabilities make it ideally suited for transport in difficult access areas, winching operations and take-off and landing at unprepared sites. In these frequently encountered and demanding mission elements the pilot faces an increase in workload when scanning for obstacles and monitoring helicopter state. Especially in degraded visual conditions and unknown or confined areas, there's an imminent danger of collision with all kinds of obstacles, which continues to be among the top causes of civil helicopter accidents. Fig. 1 depicts a recent EASA (European Aviation Safety Agency) statistic on the accident numbers per cause for civil commercial air transport in the period 2001-2010 [1].

Fig. 1. Commercial air transport accidents 2001-2010 [1].

The category with the highest number of fatalities assigned is 'Controlled Flight Into Terrain' (CFIT). When ignoring the categories concerned with loss of in-flight control and system component failure (LOC-I and SCF-NP respectively), two categories related to obstacle collisions can be seen to take up the 3rd and 5th place. The category LALT covers accidents with terrain or objects while intentionally flying close to the surface but excluding take-off and landing phases of flight. The category CTOL comprises the collision with obstacles during landing and take-off. Although the higher number of fatalities can be attributed to the higher speeds in cruise flight, collisions with obstacles during landing and take-off are clearly the main cause for commercial air transport accidents in general.

An important contribution to the above statistics are challenges typical for commercial operations such as Helicopter Emergency Medical Services (HEMS) for which landings in unknown, unprepared environments are part of the daily routine. Additional stress related to the urgency of the situation or deteriorating weather conditions compromises safety even further.

The aforementioned statistics once more reveal the need for a system which supports the pilot or crew in the obstacle detection task. For this purpose, various systems have been developed using a wide range of active sensing technologies. The majority of systems, however, come at a high cost often combined with a large physical size and power consumption. These systems are therefore mainly deployed on military platforms. The research project described in this paper aims at developing a miniaturized, low-cost obstacle warning system specifically for civil operators.

2. SITA RESEARCH PROJECT

In 2010, Eurocopter Germany initiated a research project under the name of "SITA" - **SIT**uational **A**wareness [2]. The objective of this research project is to develop a near field obstacle warning system affordable for civil operators. The novel aspect in this project is the use of automotive radar technology to develop a low-cost system and to minimize sensor size, weight and power (SWaP).

The SITA project is a logical continuation of Eurocopter's permanent efforts to develop innovative solutions to enhance flight safety [3].

The SITA project is supported by the German Federal Ministry of Economics and Technology (BMWi) in the frame of the Aeronautical Research Programme IV (LuFo IV). In the SITA consortium various partners from the German aerospace and automotive industry contribute with their specific knowledge and expertise. For the two year project duration the aim was set to develop a system concept, elaborate on system architecture and to validate the automotive radar technology in ground and flight tests.

The work was structured in various work-packages focusing on system design, sensor design, testing and validation.

3. SITA SYSTEM DESIGN

3.1. Intended Function

The SITA system is intended to enhance flight safety in approach, landing and take-off phases of flight by informing the pilot of obstacles in the near vicinity of the aircraft even in degraded visual conditions. The SITA system must not be considered as a primary flight instrument and shall only be relied upon to perform approximation procedures. The SITA system is therefore a flight aid for the pilot operating under visual flight rules (VFR). The latter limitation implies that evading manoeuvres shall only be taken after visual verification of the system indication and that these indications are to be interpreted as 'advisory'. The SITA system enhances flight safety by improving the probability of detection of obstacles.

The following operational use cases have been identified for the SITA system:

- Landing and take-off in unprepared, unknown areas.
- Landing and take-off in confined areas.
- Landing and take-off in degraded visual conditions.
- Operations in hover and confined areas.

These use cases, which are characterized by flying at relatively low airspeeds and altitude, are most critical according to the accident statistics in Fig. 1. From these use cases various key design parameters can be derived. The typical low airspeed together with a prescribed warning time, effectively determines the required detection range of the sensing system. To accommodate for the various degrees of freedom and procedures in these flight phases, the sensor system shall detect obstacles approaching the helicopter from every direction in azimuth as well as from below the helicopter. To ensure operations in degraded visual conditions requires an all-weather sensing technology not impaired by any atmospheric conditions.

The SITA system is considered to be of particular benefit to the following missions:

- HEMS missions (e.g. for emergency medical assistance).
- Offshore missions (e.g. transport to and from oil rigs cf. Fig. 2, wind park maintenance).
- Utility missions (e.g. power line maintenance, forestry, fire fighting).

Fig. 2. EC135 on an offshore mission.

Civil operators performing the above missions are typically operating small to medium sized helicopters. Limiting the primary applicability of the system to these helicopter types obviously imposes restrictions on system cost and system SWaP. Other missions are however not excluded. The SITA functions are seen to be essential for all helicopter operations both civil and military.

3.2. System Requirements

From the intended function and targeted missions the following key system requirements have been identified:

- Low-cost: the system shall be affordable for civil operators.
- Hemispherical coverage: sensor system field of view (FoV) shall cover the complete lower hemisphere.
- Near-field obstacle detection: a detection range of up to 250m shall guarantee a minimum of 10 seconds warning time below 45kts.
- Low SWaP: the system shall be integrated on small and medium sized helicopters.
- All-weather capability: the detection performance shall not be impaired by any atmospheric conditions.
- Modular and scalable system design: the design shall allow for easy extension to other platforms.
- High level of performance: the system shall have a high probability of detection and low false alarm rate. The added value of the system relies on the acceptance by the pilot.

3.3. System Architecture

The basic system design can be broken down into the following functional components (Fig. 3).

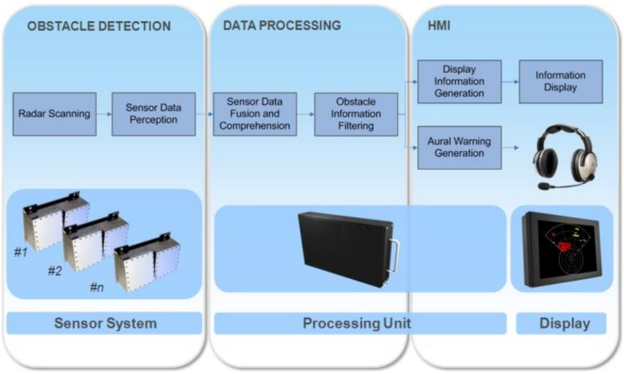

Fig. 3. Functional breakdown and system design for stand-alone (i.e. retrofittable) solution.

- **Obstacle Detection:** perception of the environment by the sensor system.
- **Data Processing:** the comprehension function in which digital radar output is processed to synthesize the obstacle environment.
- **HMI**: Human Machine Interface to present the obstacle information to the pilot through aural and visual means.

To support helicopters already in service as well as new developments, the above SITA concept can be stand-alone or integrated. In the latter concept, the data processing function can be hosted by existing processing hardware and the HMI function hosted by existing cockpit instrumentation.

For an integrated solution, also more sophisticated functions are investigated in the frame of this research project. With the aim of further reducing pilot workload, a sensor based autopilot function is developed. The direct coupling between the SITA system and the autopilot function can enable automated distance keeping and active collision avoidance. In a separate study, the fusion of the obstacles detected by the SITA system with other information from for instance an on-board obstacle database or other sensors is investigated.

3.4. Obstacle Detection Function

The obstacle detection function is the perception function performed by the radar sensor in the SITA system. Electromagnetic radio waves are emitted to illuminate the area around the helicopter. Receiver antennas shall detect the signals backscattered from objects in the scene extracting information on object location and other properties. The novelty in this research project is the use of a commercial off-the-shelf electronically steerable radar developed for automotive applications. The reasons for using this specific radar technology are multiple; it is highly optimized in terms of cost and SWaP, it is a mature technology already used for automotive obstacle detection, it has a favourable detection performance under adverse weather conditions.

To cover the complete lower hemisphere multiple miniaturized radar sensors shall be installed around the helicopter (Fig. 4).

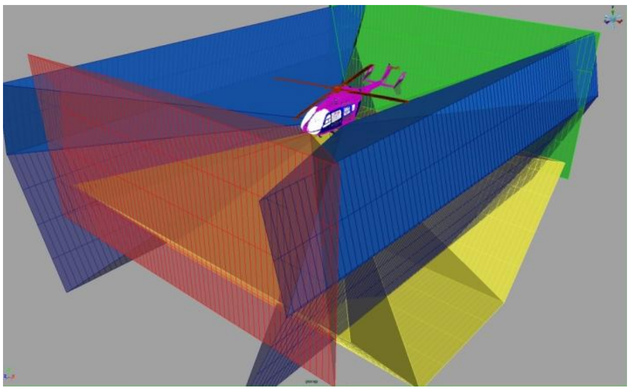

Fig. 4. Distributed sensor arrangement and sensor field of views on helicopter.

In order to remain at the low-cost level, all fabrication steps and materials used for the automotive radar are considered, while altering only the antenna for an enlarged FoV and the signal processing and data visualization.

A first prototype RF-frontend was realized using highly-integrated transmitter (Tx) and receiver (Rx) chips, which were developed originally for mass market applications at 77 GHz [4]. The complete radar module consists of several stacked printed-circuit boards (PCB). The RF-frontend PCB (Fig. 5 left) is stacked onto the signal processing PCB (Fig. 5 top right), which includes the FPGA processor and A/D converters for the 16 channel receiver array.

The horizontal aperture distribution of the radar is achieved by using digital-beamforming techniques on the receiving antenna array. For the chosen antenna arrangement, this results in an angular resolution (3 dB beamwidth) in azimuth of 4°. The beams are formed digitally, using the sampled data from the 16 receiver-channels. Typically, 15 different horizontal beams are calculated, providing an azimuthal FoV of 60°. The vertical aperture of the radar sensor consists of two beams with a vertical resolution of 5° (3dB beamwidth) resulting in a vertical FoV of 10°.

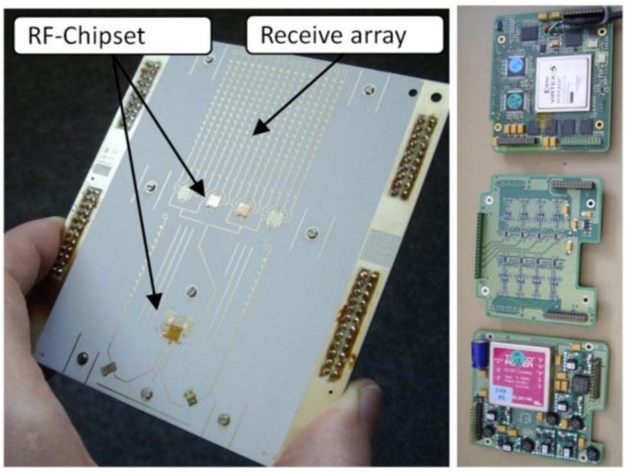

Fig. 5. Fabricated RF-frontend with RF-chipset, an antenna-array (left) and PCBs for complete sensor (right).

For object discrimination, the frequency modulated continuous wave (FMCW) principle of operation provides simultaneously the echo-amplitude and velocity information for each range-gate within a radar beam. A fast linear frequency modulated waveform is applied to the transmit-signal, thus avoiding range-doppler ambiguity within the baseband signal. The resulting output is a range-doppler (or range-velocity) matrix for every beam. The beam data is subsequently fed to the main signal processing function for object extraction.

In order to evaluate this technology, a first radar prototype has been constructed of two individual sensors (Fig. 6). To enlarge the vertical FoV, the sensors are tilted mechanically resulting in a vertical FoV of 20° and 60° in azimuth. In this prototypical configuration, one sensor has a RF-output power of 20dBm, a size of approximately 13x14x3cm^3 and a power consumption of 12W. This prototype radar has been evaluated successfully during ground and flight tests (see Section 4).

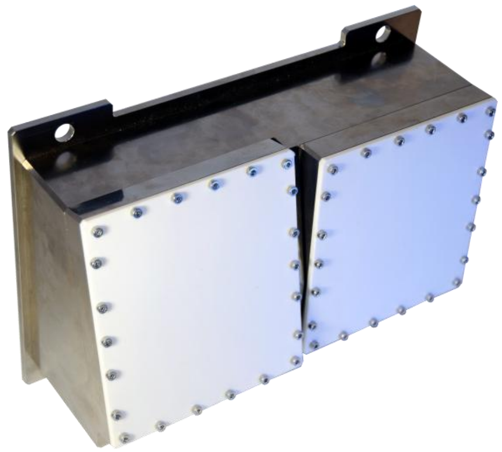

Fig. 6. SITA radar prototype consisting of two tilted sensors.

3.5. Data Processing

The data processing function is the comprehension function, in which digital radar output is processed to synthesize the obstacle environment. This conversion of radar beam data into comprehensible object data is the association step between perception of the environment and subsequent visualization. The processing contains the filtering of irrelevant information and the generation of 3D obstacles.

For each beam of the antenna, the sensor output provides a set of voxels (volumetric pixels) with the associated reflection intensity, velocity and range information. In a first step, voxels with irrelevant values are filtered out to reduce the data load. These can be noisy voxels or information insignificant for the current flight phase or the display concept. The remaining voxels are then merged into 3D volumes, where a fast clustering algorithm locates connected components to be considered as obstacle candidates. A threshold filter applied for the size of the group volumes eventually generates 3D obstacles in form of a bounding-box or 3D mesh data (Fig. 7).

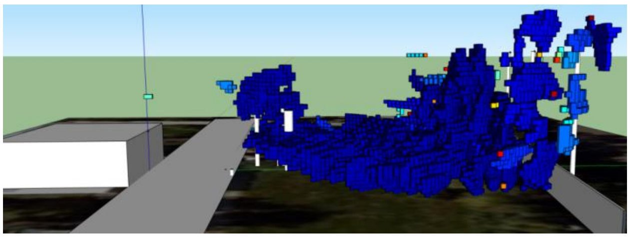

Fig. 7. Example of generated 3D-mesh in a scene (offline visualization).

In the current design phase, the algorithms were implemented using a graphics processing unit (GPU) acceleration based on compute unified device architecture (CUDA). This GPU programming framework allows access to hardware-accelerated components in a highly parallel fashion. Parallelizing the computations was necessary to ensure real-time operations. Compared to a computation mode for which only the central processing unit (CPU) is used, significant speed-up factors were achieved due to the highly parallel nature of computations involved. Nevertheless, the high data flow is a demanding challenge for the processing function. Further activities will need to focus on the optimization of processing steps and hardware allocation.

For demonstration purposes, a 2D visualization mode was developed for each individual horizontal scan (Fig. 9). This real-time processing software was used on a laptop as a portable solution to assess radar plots during ground and flight tests. To construct a 2D radar plot, the range-velocity information is converted from a polar coordinate system in an image-like Cartesian system.

3.6. HMI

The biggest challenge for the HMI consists of presenting the detected 3D obstacle environment to the pilot using low-cost cockpit elements. The principle solution for the stand-alone solution is to use an additional display (5.7”) with a high resolution screen (Fig. 16). For a more integrated solution, also existing displays may be used. An image is displayed on the screen with the helicopter fixed in the centre and the detected obstacles around the helicopter (flat, top view). The obstacles are displayed using clusters of pixels; the size of a cluster depending on the size of the obstacle and the distance towards the helicopter.

Besides informing the pilot of the existence of a nearby obstacle, also the threat potential of each obstacle is relayed, using amber for caution and red for warning. The volume around the helicopter under observation is divided into two separate volumes; a caution volume and a warning volume. The outer caution volume is limited by the radar limits and the warning volume, whereby the size and shape of the warning volume depends on the direction and speed of flight. Thus, the obstacles are displayed and alarms are given using the (changing) distance to the helicopter as well as the relative height. The display of the entire obstacle scene is also depending on the airspeed - automatically zooming in at lower speeds - although this may be overruled by the pilot.

The precise behaviour of the division of the two volumes as well as the optimum location of the additional display in the cockpit is under investigation and will be amongst the outcome of the simulator experiments (see Section 5). Another result of these simulations will be the appropriate aural alarms.

In order to optimize the parameters of the display for further challenges, e.g. the differentiation between obstacles and surrounding area (i.e. ground), additional cockpit simulation assessments are planned.

4. SITA SENSOR DEMONSTRATIONS

During the course of the project the prototype radar sensor was extensively tested. After first validation tests of the RF-frontend in an anechoic chamber, several campaigns were set up to validate the sensor performance of the first radar prototype. The aim of these tests was to validate basic sensor characteristics and detection performance. The SITA project was concluded with a series of flight tests on Eurocopter’s research helicopter to evaluate sensor performance in flight.

4.1. Ground Based Field Tests

In a series of ground tests basic sensor characteristics and detection performance were evaluated. The aim was to characterize the sensor performance for a wide range of operating conditions and obstacle environments. Especially, the detection performance for obstacles that pose a threat to helicopter operations at low altitude was analysed. Typical obstacles that are easily overlooked by the pilot are thin horizontal obstacles (e.g. suspended cables, overhead power lines) or thin vertical obstacles (e.g. trees, lamp posts).

Relevant obstacles were recorded with both the sensor mounted on a tripod (static tests) and on a moving car (dynamic tests). The prototype setup is depicted in Fig. 8. Two slightly tilted radar sensors, an optical camera and an altitude heading reference system (AHRS) are mounted on a tripod. The setup is connected to a laptop for real-time visualization through a universal serial bus (USB) connection.

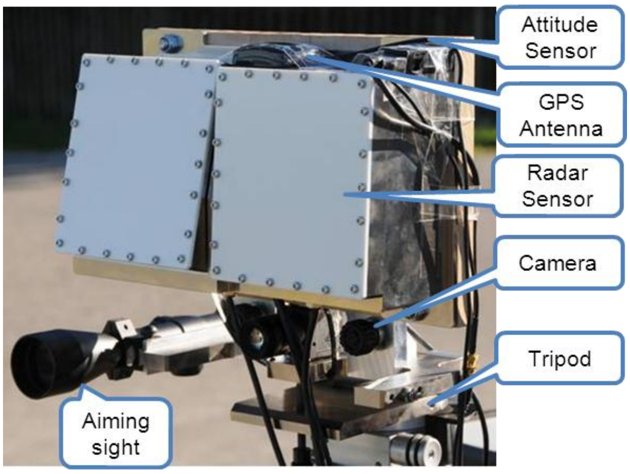

Fig. 8. Setup of the radar prototype for static field tests.

In a first example, the detection performance for overland power lines was tested. Measurements were made at various distances and viewing angles. In Fig. 9, the 2D radar plot of a singular horizontal scan is shown with colour coded display of reflected signal intensity. The measurements show a clear dependency of the intensity of the reflections on the angle of incidence. The wires reflect best when viewed perpendicular to the power line. The elevation is more or less irrelevant as the wire is round and should reflect equally for all elevation angles. For the perpendicular measurement, the intensity of the power line reflection is well above the noise floor at a distance of 240m. Viewing the power line at an oblique angle significantly reduces the reflection.

The reflections are still clearly distinguishable from the noise floor in a single scan, but the signal-to-noise ratio is decreasing and a consistent detection cannot be guaranteed when standard thresholding and filtering rules are applied for obstacle extraction. In order to improve the probability of detection the accumulation of radar measurements over time is investigated.

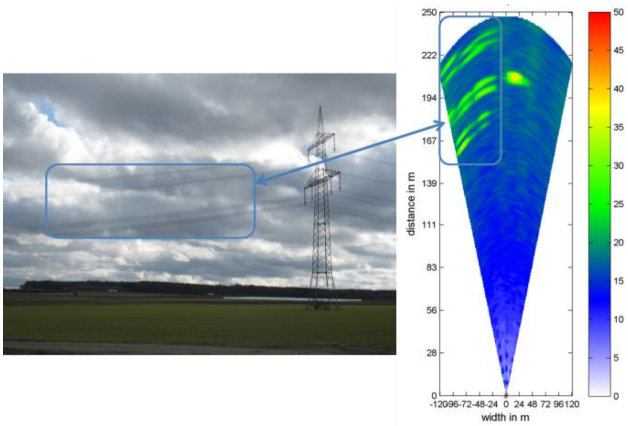

Fig. 9. Measured 2D radar plots (width and distance correspond to x- and y-axis) showing the raw reflected intensities in dB of 6 overhead power lines in a distance of 150m to 240m.

Also, measurements of more complex obstacle environments were performed. Fig. 10 illustrates the radar plot for a complex scenario together with the corresponding camera image. In a single horizontal scan various objects can clearly be located in the radar plot.

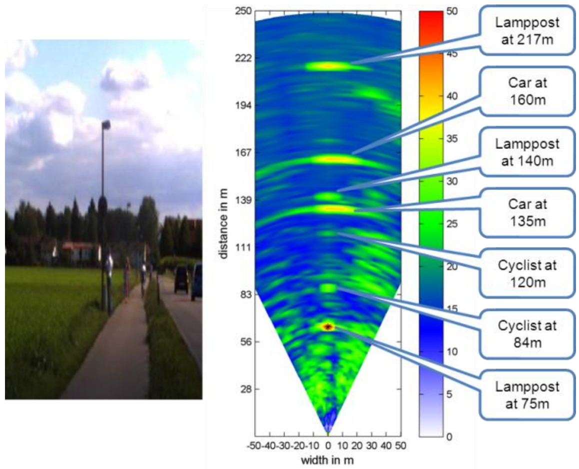

Fig. 10. Measured 2D radar plot of several relevant vertical obstacles with corresponding camera image.

In order to evaluate the benefits using accumulation of the radar echoes and to investigate the stability of the radar measurements over time, further experiments with the sensor system on a moving platform were carried out. In this scenario, additional information from an inertial measurement unit is obtained, which can be used to accumulate the radar data also GPS-based. The measurements were carried out using a car setup (i.e. radar sensor, camera, AHRS sensor mounted on the roof of a car). The car was driving at relatively low speed (i.e. about 15 km/h) on a parking lot. Consecutive measurements were accumulated to investigate the effect on obstacle detection. Redundant measurements overlay each other resulting in solid obstacles (e.g. line of trees and lamp post). Measurements from a single shot are usually much sparser making it difficult to recognizing these as true obstacles. A further advantage of such an accumulation is the ability to filter out ghost obstacles. Small reflections with high intensities in the radar plot can filtered out if they do not consistently appear in multiple consecutive measurements (Fig. 11).

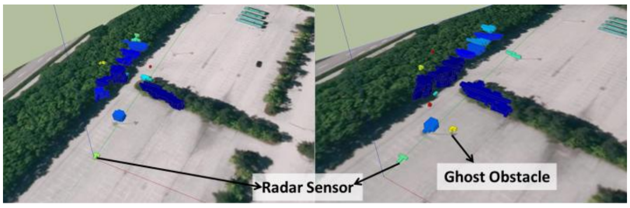

Fig. 11. 3D Mesh data of consecutive radar plots with ghost obstacles.

These and other accumulation concepts were evaluated but need to be studied further as to successfully increase probability of detection and reduce false alarms.

4.2. Flight Tests

As a conclusion of the SITA project the radar prototype was put into flight beginning of 2012. The aim was to test the radar performance on the actual platform under realistic conditions. More than 4 hours of flight testing were accumulated. The installation on Eurocopter's own EC145 research test bed is depicted in Fig. 12. The radar was attached to a multifunction mount on the right landing skid of the helicopter. The processing for 2D visualization and recording of camera and radar data were performed on a laptop located in the helicopter cabin. A synchronisation of camera and radar data enabled the offline assessment of sensor performance. Further flight test instrumentation contained aircraft state and sensor attitude in flight.

Fig. 12. SITA mounted on EC145 research test bed.

Again, a variety of obstacles including power lines, antennas, terrain contours and wind turbines were observed in varying flight conditions and manoeuvres. The different test scenarios were designed to represent closely the use cases for which the SITA system is intended (e.g. hovering in front of a rock face). In Fig. 13 the radar plots of two scenes are shown. The left plot shows the reflection of a rock face with a tree line on top in approximately 120m distance. The intensity of the reflection is continuous in azimuth and rises significantly above the noise floor. The wind turbine can also be clearly recognized in the radar plot. Even single rotating blades were visible in the radar output.

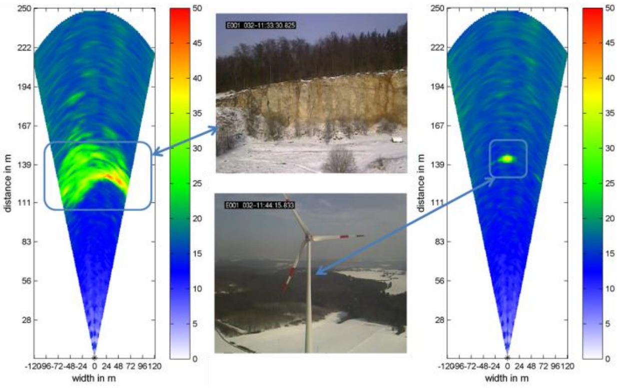

Fig. 13. Flight test 2D radar plots showing the raw reflected intensities in dB of a rock face at ~120m distance (left) and a wind turbine at ~140m distance (right).

During the various test flights the radar sensor behaved as expected and a first analysis has shown promising results having shown no unexpected behaviour or limitations of the sensor. Further analysis of the large amount of recorded data is planned with the focus on the evaluation of accumulation techniques for the system in flight.

4.3. Sensor Performance Under Degraded Visual Conditions

To validate the capability of the SITA sensor to confidently detect obstacles in degraded visual conditions, the effect of various atmospheric properties on sensor performance was examined. At the operating frequency in W-band the atmospheric attenuation in clear air is not significant for the relatively short range SITA application. However, the effects of precipitation and particulates suspended in the atmosphere such as rain, fog, dust and snow are known to have some impact [5]. Therefore, dedicated investigations were performed with the SITA sensor. For this purpose a controlled measurement volume was created in a tent equipped with the necessary test instrumentation and installations for reconstructing different weather phenomena (Fig. 14). Since the weather conditions prevented the creation of snow, the tests were limited to measurements of attenuation due to rain, fog and dust. Two corner reflectors were placed behind the tent as the reference objects to be measured. In addition, optical sensors were placed in the measurement volume to measure visibility whereas a programmable network analyser (PNA) was used

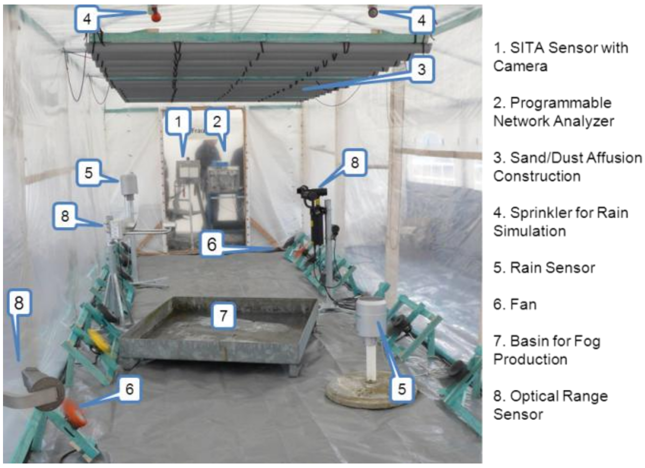

Fig. 14. Test setup for measurement of atmospheric attenuation.

as a high precision reference for the reflected signal. The results of the tests were promising as had been expected from literature studies. In most instances, no or only minimal attenuation of the reflected signal was measured. Solely inordinate high rainfall rates led to significant reduction of the reflection intensity. The all-weather capability of the chosen technology has hereby been validated for the SITA application.

5. DEVELOPMENT AND VERIFICATION OF THE SITA SYSTEM IN A DEMONSTRATION COCKPIT

The HMI concept for SITA was developed inside the **De**monstration **Co**ckpit (DeCo) which is a flight simulator cockpit with outside scene simulation (see Fig. 15). Both system architecture and computer platforms in DeCo are identical to the EC145 test bed. Thanks to this similarity, the DeCo is ideally suited to develop and thoroughly test functions or complete systems before being put into flight.

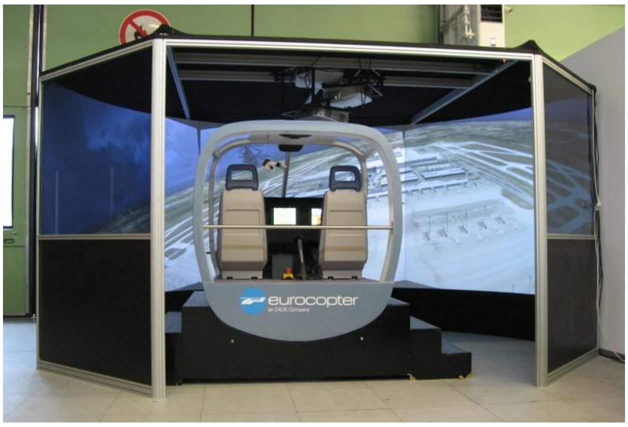

Fig. 15. Demonstration Cockpit DeCo.

In the SITA project, a radar sensor model was developed to match the actual sensor's properties. In a simulation, a total of 6 simulated sensors were placed on a virtual helicopter model covering the lower hemisphere. The inputs for these sensor models are range images of the environment generated with the use of the Eurocopter Virtual Environment (EVE). In Fig. 16, the sensor installation and an example of the range image input is demonstrated. The complete functional chain is implemented and the obstacle environment is displayed on a separate display.

Besides using this simulation for HMI loops also more advanced functions such as sensor supported autopilot functions can be easily implemented and tested. The challenge in simulating the SITA system has been to tune hardware and software to have a real-time simulation of the complete functional chain. The large amount of data from the sensors bringing interfaces and processing power to their limits

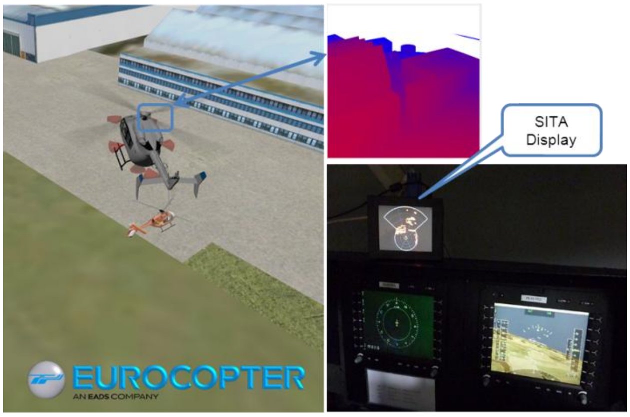

Fig. 16. Sensor Installation in EVE (left), an example of the range image input (upper right), the additional SITA HMI display (lower right).

6. CONCLUSION

Within the SITA research project, the application of automotive radar technology for use in a heliborne, near field obstacle warning system was investigated. A first system architecture was elaborated and sensor system requirements were specified. A first prototype sensor was realized by the adaptation of an automotive radar sensor. This prototype was extensively tested in both ground and flight tests. In these tests, basic sensor performance and detection performance were evaluated for a variety of obstacles typically compromising safe helicopter operations. Although not entirely processed, the results so far have been very much in line with the expectations. Basic detection performance has shown to be very promising. The biggest challenge confirmed to be the detection of wires or suspended cables. Further development of accumulation algorithms is however expected to improve the detection performance.

Many challenges were identified during the course of the project especially with respect to sensor miniaturization and integration, interface and data processing. Nevertheless, the promising results of the SITA initiative have convinced the project team and sponsors to face these challenges and to prolong the work on this concept. In the extension of the SITA project, for which activities have already started, the main focus will be on the further development of the radar technology and the realisation of a complete sensor array as well as the optimisation of the HMI. The objective is to attain a level of maturity that can mark the start of system development.

7. ABBREVIATIONS

2/3D	2/3 Dimensional
A/D	Analog to Digital
AHRS	Attitude Heading Reference System
BMWi	Bundesministerium für Wirtschaft und Technik
CFIT	Controlled Flight Into Terrain
CUDA	Compute Unified Device Architecture
dB	Decibel
DeCo	Demonstration Cockpit
EASA	European Aviation Safety Agency
EVE	Eurocopter Virtual Environment
FHR	Fraunhofer Institut für Hochfrequenztechnik und Radartechnik
FoV	Field of View
FMCW	Frequency Modulated Continuous Wave
FPGA	Field Programmable Gated Array
GPU	Graphics Processing Unit
HEMS	Helicopter Emergency Services
HMI	Human Machine Interface
PCB	Printed Circuit Board
PNA	Programmable Network Analyser
RF	Radio Frequency
Rx	Receive
SITA	Situational Awareness
SWaP	Size, Weight and Power
Tx	Transmit
USB	Universal Serial Bus
VFR	Visual Flight Rules

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