Visualisation of the brownout phenomenon, integration and test on a helicopter flight simulator

T. Gerlach
torsten.gerlach@dlr.de
Institute of Flight Systems
Department of Flight Dynamics and Simulation
German Aerospace Center (DLR)
Braunschweig
Germany

ABSTRACT

Flying under degraded visual environments is a challenging task in helicopter operations. The brownout phenomenon, caused by the rotor downwash on a dusty or sandy underground has caused several critical incidences and accidents in the past. In contrast to an extensive free wake analysis of the rotor vortices, this paper presents a computer graphical solution to simulate brownout conditions. The animation approach builds upon a particle system with a basic aerodynamic assumption of a permanent ground vortex and additional turbulence. The created brownout effect module is a part of the RealTime Image Generator software, used in DLR's ground based helicopter flight simulator. The object oriented structure of the underlying application programming interface OpenSceneGraph facilitates the development of a generic effect interface for future improvements. An overview of the developed module, the particle system engine and the physical dependencies is provided. To overcome the challenge of capturing the visual realism, a pilot test course with brownout typical tasks is presented. Criteria focussing on the visual and physical parameters are defined to build up a questionnaire. It is used to improve the visual standard and to meet the future pilot's needs.

NOMENCLATURE

API	application programming interface
ALLFlight	assisted low level flight and landing on unprepared sites
CPU	central processing unit
DARPA	Defense Advanced Research Projects Agency
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
DVE	degraded visual environment
FHS	flying helicopter simulator
GPU	graphics processing unit
IG	image generator
LOD	level of detail
ms	milliseconds
NASA	National Aeronautics Space Administration
OGE	out of ground effect distance
OpenGL	open graphics library
OSG	open scene graph
RTIG	realtime image generator
UCE	usable cue environment
UML	unified modelling language
XML	extensible markup language

1.0 INTRODUCTION

The helicopter with its flexible operational envelope is a fascinating vehicle. In particular, the abilities of vertical flight and hover made it an important part of modern aviation. These abilities, however, lead to some critical situations for the pilot, when flying near the ground, in darkness or dusty environments. Especially, the so called brownout/whiteout effect is encountered more often in military operations, because of the increased number of missions in desert regions.

The minimisation of the risk potential under such operation conditions is a current research topic. Therefore, the German Aerospace

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Figure 1. Flying Helicopter Simulator (FHS).

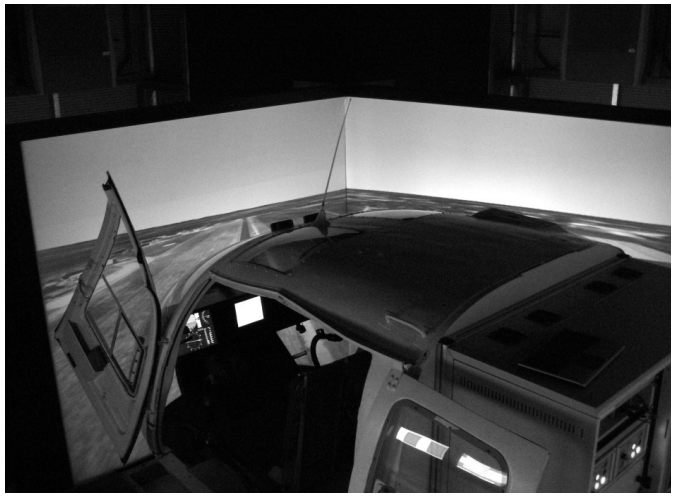


Figure 2. FHS ground simulator.

Center (DLR) initiated the helicopter research program ALLFlight (assisted low level flight and landing on unprepared sites) in 2008. ALLFlight analyzes the use of modern sensor systems, new flight controllers, enhanced flight guidance displays and haptic cue information for the pilot in degraded visual environments (DVE). For development and evaluation purposes, the DLR uses the Flying Helicopter Simulator (FHS), a modified Eurocopter EC-135 with the ability to act as an inflight simulator (Fig. 1). It is equipped with a separate onboard computer system that can recompute actuator commands and controls special user dependent displays in experimental mode.

To safely prepare and test experimental algorithms and system configurations, a ground based simulator (Fig. 2) was developed. It is a replica of the real helicopter and simulates the dynamic behaviour, real environment and steering controls through modern simulation methods and technologies[1].

For the support of ALLFlight's real flight experiments, miscellaneous DVE-scenarios will be integrated into the ground simulator. Because the risk of a brownout in flight is not assessable in advance, this effect is only implemented into the simulator.

The simulation and visualisation of the dust entrainment through rotor down wash is a complex task that can be done by several concepts. The focus of this implementation is to generate a realistic visual representation for the pilot. This can be achieved by using the particle system concept. Particle systems are used to model fuzzy natural phenomena, where each particle presents a certain granular part of the complete system, e.g. dust matter. The physical motion computation is based on Newtonian laws, where the rotor downwash is the primary interacting force.

The following sections give an insight into the development process of the brownout module for DLR's render engine and the evaluation of a simulator test with helicopter pilots flying at a virtual version of Braunschweig's airport.

2.0 THE BROWNOUT PHENOMENON

The term brownout implies the visual degradation through dust entrainment caused by the rotor downwash of helicopters or landing aeroplanes. It is also referred to as whiteout, if snow is blown up in the air. Usually, a pilot tries to avoid such situations, but today's military operations are often carried out in desert regions. Typical critical flight manoeuvres are landing, take off or low level slow forward flight. Figure 3 shows the evolving brownout dust cloud of a MV-22 Osprey during a landing approach.

To support the pilot during critical situations, special cockpit instrumentation and advanced sensor systems have been introduced in commonly used helicopters. For example, DARPA's Sandblaster program[2] uses radar and laser sensors to build up a synthetic view of the outside world.



Figure 3. MV-22 Osprey landing approach[2].

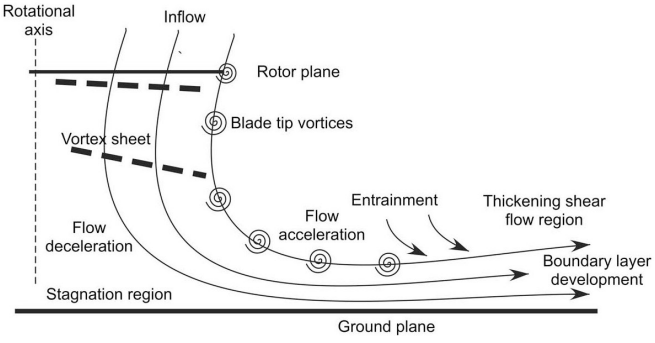


Figure 4. Schematic vortex distribution[5].

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The formation of a brownout cloud is the result of interaction between rotor wash with the ground. Loose matter, e.g. dust particles, is entrained from the surface and forms a dense cloud that is sucked back by the rotor. Density and duration of the cloud depends on the surface material and rotor vortex distribution. The interaction with the ground plays a key role in the cloud formation. In ground effect (see Ref. (3)), the rotor induced thrust from the ground vortex; blade tip vortices keep formed and move along the rotor wash flow to the ground. Figure 4 shows the schematic vortex distribution under the rotor near the ground plane.

An important variable is the out of ground effect (OGE) distance. It expresses the altitude, where the ground effect looses influence on the rotor, because of the missing wake distribution between rotor disk and ground. OGE distance can be computed with helicopter's rotor radius and an experimental identified constant[4]. The brownout module uses this value for the beginning dust cloud formation.

The available computing power of modern systems makes it possible to use complex models for an accurate dust cloud prediction. Methods of fluid dynamics included in research applications and commercially tools are widely used for specifying helicopter rotor characteristics. The used models combine rotor down wash prediction algorithms with numerical or analytical physical surface models[6,7,5]. Generally, those computations are very time consuming. A different way was adopted by Continuum Dynamics Inc. Their physics based model uses a free wake analysis tool called Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM) and couples it with a debris transport model[8]. This led to a real time capable module for the external integration into flight simulators.

3.0 BROWNOUT EFFECT MODULE

Developing a visual effect module is, in general, a difficult task, because of its dependencies on available hardware and software. However, some generalised aspects can be identified:

- The dynamic helicopter simulation must provide data for particle force interaction.
- The software concept of the module must be object oriented to fit into existing code base.
- The module must provide a sufficient configurability for mission specific dependencies, e.g. desert environments.

Because of the real time environment, the module needs to finish all computations in a cycle time under 20 milliseconds, to create a realistic animation. The above requirements bring up three main components of the visual effect module.

1. rotor down wash
2. surface and erosion model
3. particle and dust cloud visualisation

3.1 Animation concept

The DLR's dynamic EC-135 model does not include a simulation of vortex characteristics. The only source of thrust force is given indirectly through engine torque. Further parameters like helicopter position and attitude are already available in the visual system.

A precise erosion model of surface matter is also not available. A new model had to be developed in conjunction with the existing terrain database. Satellite and aerial photos are available.

The computer graphical visualisation is a complex task and needs to be handled carefully. To get a realistic appearance of the dust cloud several concepts are possible. Because of the simple and natural principle of particle systems, this concept is chosen for the brownout visualisation.

For decades, particle systems exist in the computer graphics world. The first scientific paper was published by W.T. Reeves in 1983[9] and visualised a fire wall moving around a planet. The fire was made of hierarchical particle systems.

Usually there are three main parts that build up a particle system also referred to as particle engine:

1. Management
2. Particle
3. Dynamic behaviour

The management component controls the life cycle of a particle and the cyclic particle update.

A particle describes a physical and visual state at a defined time. It has standard attributes like position, velocity, lifetime, visual attributes, e.g., shape, colour or texture and physical attributes like size and mass. The emission process is done by a separate module. Such an emitter ejects particles in a specific area and initialises motion through setting velocity and direction. Generally, stochastic functions are used to place particles in a natural manner. After emission, the update process recomputes particle velocity $v(t)$ and position $p(t)$ through differentiation (Equations (1) and (2)) and the second Newtonian Law, where particle acceleration a depends on force f and mass m (Equation (3)).

$$v(t) = v_{t-1} + a \cdot dt \quad \ldots (1)$$

$$p(t) = p_{t-1} + v \cdot dt \quad \ldots (2)$$

$$f = m * a \Rightarrow a = f/m \quad \ldots (3)$$

To ensure animation speed and low memory requirements, the explicit Euler integration method with a small step size, typically 10ms, is used.

After setting up the particle engine, any external force can be applied to a single particle, e.g. gravity, air resistance or damping. Another interesting effect is collision detection and response with solid surfaces.

The combination of a huge number of particles animated through external forces visualises natural phenomena like a waterfall or a dust cloud in a realistic way.

Figure 5 shows the influencing factors on a particle in the brownout animation model. The ground vortex specifies a rotating force on the emitted and living particle. The emission area is fixed at the rotor axis and guarantees a permanent ejection in the vortex area.

3.2 Ground vortex and turbulence

A central element for particle animation is the combination of a permanent ground vortex and an additional turbulence. Both forces depend on the helicopter's height over ground to blend both and fade the influence in or out. While turbulence is a directional force perpendicular to the rotor axis, the ground vortex is a dynamic circular force zone that has a toroid shape. It depends on the rotor radius and altitude.

The interacting force on a particle is computed with its current position around the rotor axis through simple analytical vector equations. Ground vortex and turbulence are combined and scaled with a rotor thrust coefficient which is derived from the engine torque parameter coming from the dynamic simulation. Engine thrust is computed by a linear transition function to simulate a realistic wind speed near the ground. All computations are analytical and are realised without matrix operations.

3.3 Surface model

A realistic impression of entrained dust material needs a flexible surface definition model. Local structures like rocks or roads have to be

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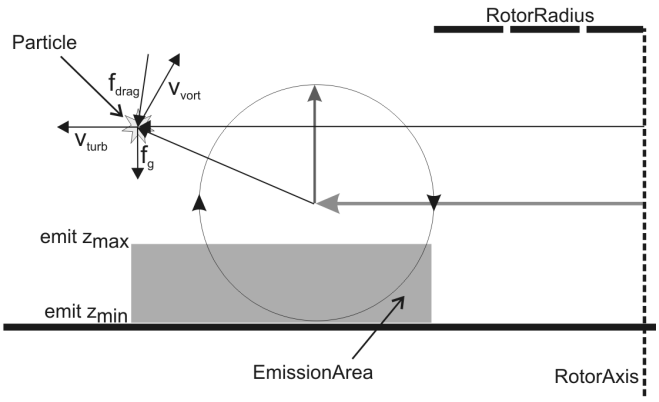


Figure 5. Particle forces.

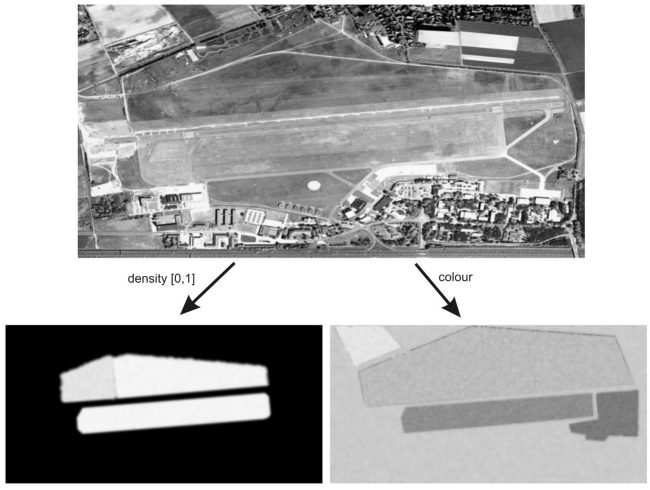


Figure 6. Surface model: density and particle colour.

taken into account. The particle entrainment marks an erosion process, where particles settle down after a defined amount of time which was derived from empirical measurements. Another requirement is the local colour and density of the surface material. A double staged approach for colour and density is used. Both use a two-dimensional array. They can be generated through a texture that is derived from a real aerial photo of the region. Figure 6 presents a photo of Braunschweig Research Airport that was used for testing and development of the brownout module. The creation of the density and colour map was done by hand by a conventional image editing software.

The density map consists of a greyscale image that stores the amount of dust in a range between 0·0 and 1·0. To get a realistic distribution, noise is added and a Gaussian filter was applied to smooth the transitions. The colour black corresponds to no surface matter, whereas white is the full density. If the density value of a particle is computed from the map, the value becomes a part of its own colour alpha value. The colour map is a 24bit image to allow the use of every imaginable particle colour. Also noise and Gaussian blur was applied to create an inhomogeneous surface appearance.

To complete the simulation of this natural process, a self-developed erosion and settlement algorithm is applied. Each time a particle is emitted, the density map reduces the actual value at particles position. Because of the frame rate dependent scheduled emission, lots of particles are emitted and can therefore reduce the density to zero. An asynchronous particle settlement function increases the amount of the complete map in discrete surface material units to the original values. The amount is controllable via parameters. A return and usage of a previously completely dust free area is thus possible.

3.4 Particle visualisation

Since a manoeuvre in brownout typical environments usually creates a large dust cloud, a huge number of particles have to be emitted and visualised. To ensure a good rendering performance, a single particle pretends to be a larger material group. A particle is drawn by a single quad that uses the computer graphical billboard principle. The used billboards automatically align their face to the eye point through angle calculations around their centre point. The visual representation is done by modulating a texture to the geometric quad. The texture has white and transparent blurred areas. The particle engine that is used for the brownout module uses the same texture for every particle. To provide a realistic impression it is necessary to avoid noticeable regular structures. In particular the edges have to be fully transparent. The creation of a suitable texture can be done with procedural techniques, e.g. Perlin Noise (See Ref (10)), or with image manipulation software. The realistic representation is achieved by using the density and colour map from the surface model. Before particle emission, a certain alpha and colour value is computed from the ground definition. Additionally, the particle engine fades particles in and out, so that a life cycle from surface entrainment to settlement is animated.

4.0 SIMULATOR INTEGRATION

The software integration into the existing render engine is done by extending the available software structures. Institute of Flight Systems uses an OpenGL based render engine which is build upon the scene graph API OpenSceneGraph (OSG).

OSG is a freely available C++ application programming interface (API) with an object oriented concept. The focus lies on reusability and extensibility of all software components. Around a base core, several NodeKit libraries are arranged. OSG supports multi core CPU and multi GPU rendering, plug-ins for a huge number of 2D and 3D formats, has a built in particle engine, a visual effects module and a platform independent window toolkit. Through the extensible concept a developer is able to change the source code and create his own modules.

The virtual environment for the ground simulator is created by the RealTime Image Generator (RTIG). This software is built on top of OSG. The software concept is modular and allows the use of API like structures or a binary version for the IG installation. Because of the wide spread use, from multi channel visual systems to desktop visualisation, the software can be externally configured to have a scalable performance. Configuration is done by XML, which is a standardised text based mark-up language, with an application specific syntax. Some further features are a paged LOD database, multiple dynamic 3D objects and a built-in warping API for edge blending and distortion correction.

For integrating the brownout module, a special interface must be created. The interface has to be configurable through the existing XML parser, must not be brownout specific in order to support visual effects developed in the future, and must be object oriented with a clear discrimination between physical computation and graphical rendering.

A central part of the effect module is the particle engine to animate the dust cloud. As OSG delivers the osgParticle NodeKit, it had to be evaluated whether it fits the animation concepts needs. Typical requirements are:

- Dynamic change of forces
- Definable stochastic functions of a certain distribution
- Definable shape and appearance, life time, physical properties
- Sortable particle order

The evaluation identified the following important work steps.

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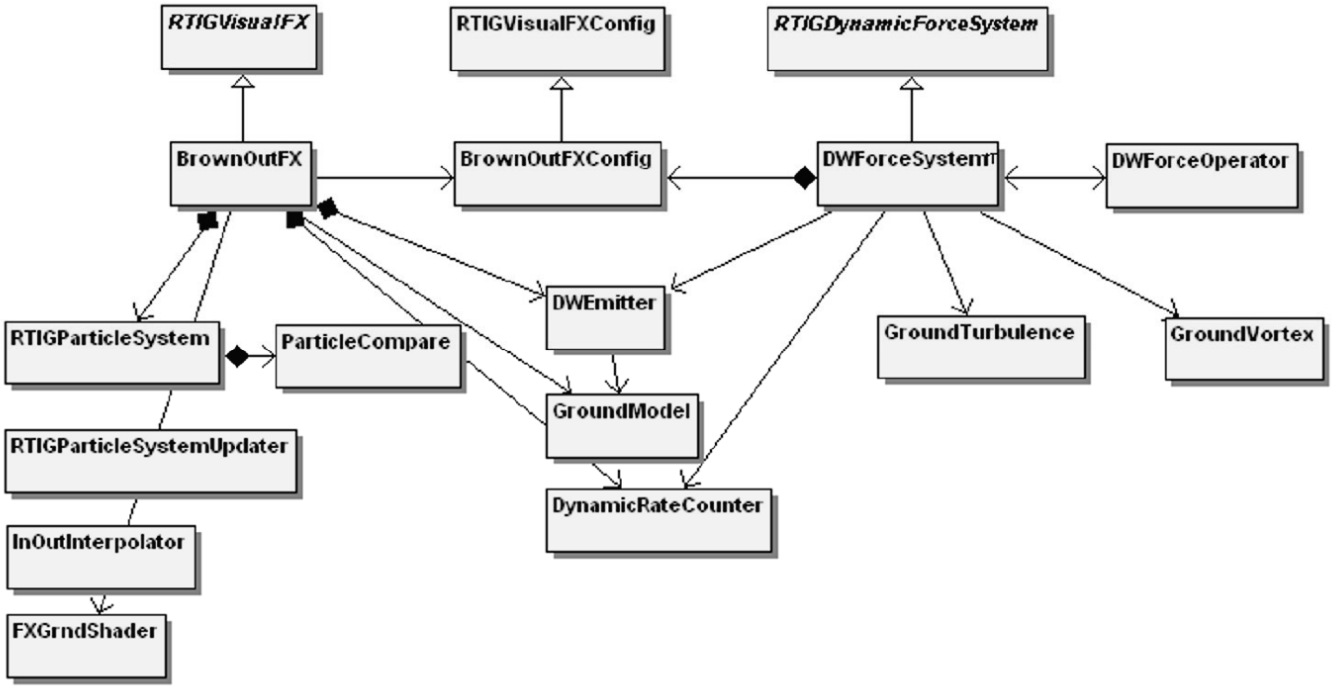


Figure 7. UML diagram BrownOutFX module.

4.1 Emitter development

A derived emitter controls the complete particle creation process. He uses the surface model and controls the erosion process.

4.2 Code changes particle classes

To avoid visual artefacts when rendering thousands of particles, a view point distance dependent sorting has to be applied. The OSG internal particle engine lacks this feature and had to be modified. The results were four changed classes with new and rearranged structures. This newer version is now incompatible to the public version.

4.3 Particle operator for physical influences

The new particle operator enables the computation of ground vortex and turbulence forces on a particle element.

To provide a reusable interface to the core render engine, an abstract interface was developed. The implemented brownout visual effect module uses this interface and integrates its components in RTIG. Figure 7 shows the UML diagram (see Ref. 11), only the class names and associations are visible, to clarify the relations between the different software parts .

The interface itself contains three classes. First, RTIGVisualFX is the main interface to the developed visual effect. It has references to system dynamic data and is a derived graphical group node. Second, the XML parser can be extended with RTIGVisualFXConfig derivatives.

Data that is special for an effect is stored in non specific arrays. Third, a force system with complex computation should use the RTIGDynamicForceSystem base class. It is a container for numerical computation and is linked with the particle operator.

The module itself is a class system for visualising the dust cloud for one thrust source. The main class BrownOutFX manages object references and the data distribution to the other parts.

The effect configuration is done in the main configuration file. Table 1 presents the possible parameters.

Table 1
XML specification

```
<visualfx type="BROWNOUT">
 <radius>Number rotorRadius</radius>
 <model>Number ModelIndex</model>
 <height>Number groundHeight</height>
 <wind>Number x, Number y, Number z </wind>
 <ground>
  <density>String densityFile </density>
  <surface>String surfaceFile </surface>
  <size>Number width, Number height </size>
  <position>Number lat, Number lon </position>
 </ground>
</visualfx>
```

The correlation between effect and dynamic animated model is done with an index parameter. It directs the objects dynamic data internally, e.g. thrust, position and attitude, to the module.

The extended render engine capabilities enable the user to use the brownout effect at any area. Because of the connection between the helicopters height, the computed OGE height from rotor radius and thrust, a realistic animation of an evolving dust cloud is obtained.

5.0 VISUAL EVALUATION

To facilitate further development and future modifications on visual effects, it is necessary to find criteria for quality and reality. Visual evaluation is commonly a subjective task that depends on the viewer, in our case the pilot. For this reason a successful integration can only be rated by the acceptance by the user.

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Evaluation criteria in simulation applications rarely focus on the visual representation. In helicopter research the Aeronautical Design Standard 33 (ADS-33)[12] is often used to determine handling qualities of pilot commands. Generally, for degraded visual environments the Useable Cue Environment (UCE) is a suitable way to evaluate the simulator performance; See Refs (13) and (14) for results of NASAs Vertical Motion Simulator (VMS) classification.

Focussing on the pure representation of a visual effect, common criteria must be discarded. A new approach with special criteria was used, to get a direct relation to visual features from the effect module.

5.1 Criteria

The following criteria build up the foundation of a pilot questionnaire.

- Visual/Animation

  Particle size, texture, number of particles, degree of occlusion, begin/end of turbulence, lifetime, dust cloud following
- Mission dependent

  Task accomplishable, increased work load, Difference to non brownout flight
- Environment specific

  Influence of the simulator on the validation

Evaluation is done on a self developed scale from 0 to 8, where 0 is poor or nothing and 8 is excellent, respectively strong. Table 2 shows a part of the questionnaire for the pilot. A scale with 9 different grades allows a fine grained analysis of the results. Additional statements from experienced pilots could be written down under evaluation, which was optional.

Table 2
Dust Cloud

How do you perceive the visualisation of the dust cloud?

Particle number/Density

Poor **Excellent**

0 1 2 3 4 5 6 7 8

Evaluation: (e.g. less at some spots, too much)

>_____

_____

The summary in Table 4 lists all criteria in a short manner. The questionnaire itself consists of five pages, where the pilot had to fill in his observations.

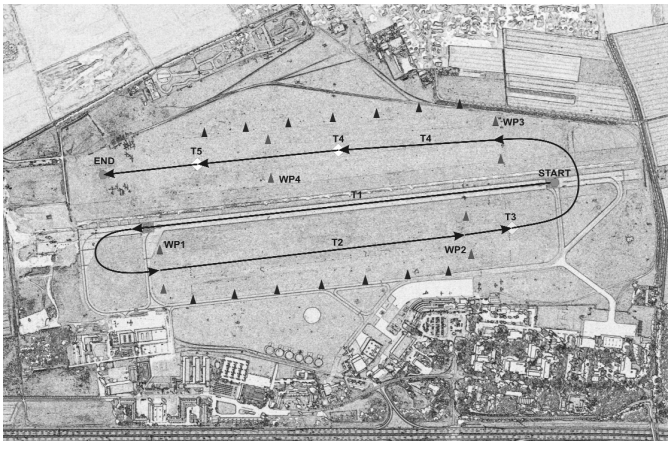


Figure 8. Brownout test course.

5.2 Scenario

Based on ADS-33, a test course with brownout typical tasks is set up. Three recurring flight conditions for brownout situations can be identified.

- Slow low level forward flight
- Low level hover
- Take off/landing approach

From the identified flight conditions, a course with five different tasks was created. Because of the airport's infrastructure, some tasks need transition passages. To get a better altitude reference, blue cones were put at the edges of the test area. The pilot can use a hover display for hovering tasks. The following Table 3 describes the pilot's tasks.

Table 3
Brownout course tasks

	Description	Ref
Start	Alt.: 500ft, Vel.: 60kts	–
Task1	Reduce speed and altitude speed to 30-40ft.	–
WP1	Start Task2	Red cones
Task2	Slow fwd. flight. 20kts in 25-35ft. Watch dust wall following	Blue cones right side
WP2	End Task2, transition to Task3	Red cones
Task3	Hover in 30ft. Watch emerging dust cloud Start fwd flight to WP3	Yellow plane –
WP3	Start Task4	Red cones
Task4	Land in front of white plane, short wait and take off to WP4	White plane
WP4	End Task 4, Start Task 5	Red cones
Task5	Land in front white plane, reduce thrust immediately, Observe clearing atmosphere, Give more thrust and blow dust away, Take off if brownout cloud vanished	White plane
End	Leave course	–

In the mission briefing the pilot gets to know the course, tasks, aspired altitudes and velocities and times for landing and take off. Figure 8 shows the desired flight path and task stations.

5.3 Simulator test

The test pilot flies the course, evaluates the virtual brownout conditions, and notes his observations afterwards. Up to now, there was one test run with two DLR pilots. Both have experiences in whiteout and nearly brownout conditions. Their type rating is Eurocopter EC-135 and MBB BO-105 with a number of pilots flying hours with 1'800 and 4,500. The OGE altitude was 30ft, the target altitude for hover and forward flight was between 20ft to 40ft. The desired speed was 20 knots, to achieve a good dust cloud generation.

Each pilot flew the course once with an instructor and filled out the questionnaire afterwards. Table 4 shows the results for visual, mission and simulator specific questions.

The last question was about the total grade of realism. It was answered with five by both pilots. The following additional statements were made after the simulator test:

- The general dust motion is too irregular
- A longer dust lifetime would make it more realistic
- Task 3 (Hover) needs an additional visual reference to the front
- The ground texture is distracting during low level forward flight, because of the different colours of ground texture and dust particles

Figure 9 presents a screen shot from an outside view of the FHS.

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Table 4
Questionnaire summary

Aspect	P1	P2	Remarks
Particle visualisation			
Size	8	4	No particles recognisable, too flaky, big
Texture	8	5	Realistic uniformity, rough textured
Transparency	8	6	Opacity realistic
Dust cloud			
Particle number/density	4	6	Improvable dynamic
Begin/end of turbulence	5	6	Front to early/sides clearly defined
Donut effect (landing manoeuvre)	6	4	Donut opens completely-> not realistic, not distinct
Visual degradation	5	6	Cloud looks fragmented; should be smoother
Cloud catching up after fast stop	7	6	Front to early; sides not close enough
Dust density at ground			
Density/Lifetime	5	7	Looking through cloud after a while–> not realistic; time should be variable
Dust cloud following in forward flight			
Dust cloud following	6	6	More noticeable wall desirable; could be more realistic with better texture and better dynamic
Mission (course und tasks)			
Task accomplishable	yes	yes	–
Increased work load	6	6	–
Work load without brownout	–	–	A flight without brownout was not done.
Simulator (influence)			
Projection system	5	5	–
Control load system	4	6	–
motion system	4	4	–

6.0 CONCLUSION

Visualisation of the brownout phenomenon with computer graphical concepts and a simple animation is possible. The visual quality of the dust cloud depends strongly on the used texture. Low turbulences lead to a coarse visual particle representation. As a consequence, a set of textures should be designed and tested. Better results could be achieved by procedural textures that change over time. Additionally, multiple textures should be used to avoid recognisable structures.

The dynamic motion and propagation of the dust cloud with the presented analytical model simulates essential effects. A better thrust dependency and more irregular distribution can produce a better dynamic. Increasing the particle life time creates an even more realistic cloud formation. A new test environment with realistic coloured surface textures will create a better simulator experience.



Figure 9. Dust cloud formation after FHS.

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