

HWIL SIMULATION IN EO DOMAIN

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ABSTRACT:

Infrared camera as a weapon sub system for automatic guidance is a key component for military carrier such as missile for example. The associated Image Processing, that controls the navigation, needs to be intensively assessed. Experimentation in the real world is very expensive. This is the main reason why hydride simulation also called HardWare In the Loop (HWIL) is more and more required nowadays.

In that field, IR projectors are able to cast IR fluxes of photons directly onto the IR camera of a given weapon system, typically a missile seeker head.

Though in laboratory, the missile is so stimulated exactly like in the real world, provided a realistic simulation tool enables to perform synthetic images to be displayed by the IR projectors. The key technical challenge is to render the synthetic images at the required frequency.

This paper focuses on OKTAL-SE experience in this domain through its product SE-FAST-HWIL. It shows the methodology and Return Of Experience from OKTAL-SE. Examples are given, in the frame of the SE-Workbench. The presentation focuses on trials on real operational complex 3D cases. In particular, two important topics, that are very sensitive with regards to IG performance, are detailed: first the 3D sea surface representation and then particle systems rendering especially to simulate flares. Beyond "projection mode", some information will be given on the SE-FAST-HWIL new capabilities dedicated to "injection mode".

1. SE-WORKBENCH-EO

1.1. Overall presentation of the SE-Workbench

The SE-WORKBENCH is a multi-sensor battlefield modelling workbench mainly used by:

- defence agencies as French DGA, German BWB, South Korea MoD, Singapore DSO/DSTA

and Swedish FOI

- research centres as ONERA, IOSB Fraunhofer Institute,
- Industrials in and out of France as MBDA, Dassault, LG, STC.

SE-WORKBENCH-EO is the infrared sensor dedicated part of the SE-WORKBENCH that achieves the synthesis of 3D scene observed by an Electro Optical (EO) sensor, in four steps:

- First, the physical characterization of the 3D scene behaviour,
- Then, the scenario edition (definition of the objects of the scenario, of the 3D scene and objects, assignment of trajectories to moving objects, definition of atmospheric and thermal conditions, parameterization of the sensors),
- Then, the computation of the physical radiance signal received by the EO sensor
- At last, the sensor effects modelling.

The SE-WORKBENCH is entirely based on software products developed by OKTAL-SE and realizes the multi-spectral unification of optronics, electromagnetism, laser and GNSS (Global Navigation Satellite System), using a common kernel and physical extensions assignment both aimed at a unique 3D scene and a common technology. The SE-WORKBENCH is a winning initiative for sharing R&D efforts and federating a user group community that intends to exchange experience and knowledge.

The first development was in 1994 and has been strongly boosted by the French SCALP missile program and the qualification of the IR tracking system. At the beginning, the SE-WORKBENCH was focused on the IR domain. In 2001, an electromagnetic version of the workshop was initiated, with the help of ONERA French research center, mainly focused on millimeter waves and wide scenes, typically for SAR applications. A GNSS version for satellite application has started in 2009.

The control of the SE-WORBENCH-EO validity domain is based on both a theoretical validation approach (development of physical models, general modelling and simulation knowledge, elementary

tests and validity assessment) and a validation process based on comparisons with experiments (SCALP/EG missile [FR], AASM missile [FR]).

1.2. The SE-WORKBENCH-EO architecture

The SE-WORKBENCH-EO is made of different components, as described hereafter, corresponding to the successive steps of a IR sensor simulation that are the modelling of the synthetic environment, the scenario edition, the rendering without the sensor effects and finally the sensor transfer function simulation. Furthermore, the user can do software integration in order to control the generated scenario execution from a remote or custom application. This can be achieved with the help of the SE-TOOLKIT consisting of a set of dedicated libraries and application programming interfaces (API) to help the complex application design and integration.

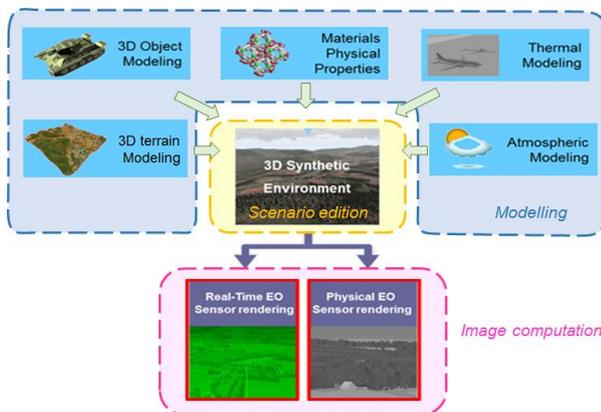


Figure 1. The SE-Workbench components

1.3. Real-time rendering based on SE-FAST-IR package

The SE-FAST-IR package is made of a major product (SE-FAST-IR) and additional modules depending on the considered application. With the help of some pre-calculation steps, real-time images are computed with the SE-FAST-IR solution. It is dedicated to the rendering of images from near infrared sensors (visible band and SWIR) to thermal infrared systems (MWIR and LWIR). The products make use of the results of the SE-PHYSICAL-EDITOR modeller and the SE-ATMOSPHERE atmospheric files computation product. The thermal pre-calculations are based on SE-THERMAL code. SE-FAST-IR brings a technological rupture by using OpenGL pixel shaders enabling direct calculation on 3D graphic cards. A shader is a procedure written in a special purpose C like language that replaces a part of the graphic pipeline of a 3D graphic board. The new core of SE-FAST-IR is based on the open source "Open Scene Graph" layer upon Open GL. When the ray tracing image is constructed pixel by pixel, the rasterized image is constructed by projection of the polygons. A given 3D polygon is projected in the

screen 2D space, the varying data that characterize this polygon, being associated to this projection. Then the polygon is split into 2D sets of pixels, called fragments, that are stored and sorted (frame buffer) in function of their depth i.e. the distance to the screen.

2. INTRODUCTION TO CONCEPTS

2.1. Non-real-time and Real-time duality

The SE-WORKBENCH-EO workshop, also called CHORALE by the French MoD/DGA, is used to perform multi-sensors simulations on complex 3D synthetic environments. The SE-WORKBENCH-EO enables the user to create virtual and realistic multi spectral 3D scenes, and generate the physical signal received by an infrared sensor. One key feature of SE-WORKBENCH-EO is the Non-real-time and Real-time duality. The technique associated to Non-real-time solution is called "ray tracing". It runs on the CPU (Central Processor Unit) of the computer and now also on the GPU (Graphical Processor Unit), in the frame of General Purpose GPU. Ray tracing consists in tracing plane waves of electromagnetic field, called rays, and, through the 3D scene, thanks to geometrical optics, managing multiple bouncing of rays and scattering effects on surfaces.

The advantage of the Non-real-time approach is that the computation is made wavelength by wavelength, that the transmission within atmosphere can be done atmosphere segment by atmosphere segment and that the interaction with surfaces can take into account very sophisticated angle and wavelength dependent models. Typically, radiative coupling between surfaces or thermal shadows (in addition to normal shadows) can be accurately simulated. Besides, Non-real-time pre-computations can be used to enrich Real-time rendering. In other words, this kind of simulation is very close to Physics.

The technique associated to Real-time solution is called "rasterization". It runs on the GPU using pixel "shaders". A shader is a piece of code that enables to control the way of drawing pixels. Rasterization consists in projecting triangles of the 3D scene onto the 2D screen and then to draw pixels to fill the triangles. It has no correlation at all with any physical process.

The advantage of real-time is the performance. For simple images, frequency of some hundreds Hz can be reached.

For HardWare In The Loop (HWIL) simulation, both techniques can be used. For open loop simulation, pre-computed sequences of images can be prepared and replayed in real-time. In this case, non-real-time rendering tools can be used.

For closed loop simulation, which is the most common case, real-time rendering is compulsory.

In all cases, this Non-real-time and Real-time duality is very important in order to assess the simplification

made in the field of Real-time rendering with regards to Non-real-time rendering.

2.2. 3D scene constraints

One other very important feature for achieving real-time aggressive performances is the full control of the 3D scene modelling. To do so, the SE-FAST-HWIL package can include three complementary modelling tools:

- SE-AGETIM product line is self-consistent with the whole SE-Workbench-EO. SE-AGETIM is a 3D terrain and modelling tool. It directly generates the complex scenes with all the Physics inside.
- SE-PHYSICAL-EDITOR tool is a physical dedicated modelling tool that gives opportunity to control the material Physics.
- SE-FFT product includes a plug-in to the standard free SketchUp Google 3D modelling tool and a plug-in 3DS Autodesk 3D modelling tool to import/modify/export 3D objects

Thanks to these tools, the 3D database can be deeply optimized in order to reach real-time performances.

Geometry constraints

The first step of simplification concerns geometry. One important part of the polygon budget concerns the terrain. SE-AGETIM includes special algorithms in order to adapt the vertices density of the meshing to the local terrain complexity. Beyond that, Level Of Detail (LOD) on the terrain are automatically computed. The terrain is first tiled. SE-AGETIM prepares several representation of these tiles from a very complex one (near observation) to a very rough one (long range observation).



Figure 2. Level Of Detail on the terrain

This is a complex process since it must take into account the features commutation (rivers, roads, forests, buildings) and avoid any hole when associating several representations at different level of detail in the same frustum. Levels Of Detail are also very important for the other features as for linear elements, surfaces and 3D objects. Concerning 3D objects and buildings in particular, several modes of representation are possible:

- the object can be geo-specific,
- the object can be an instance with many occurrences and, in this case, the LOD must be well prepared in order to save lots of polygons,
- the object footprint can be geo-specific but the elevation template can be instanced. To do so OKTAL-SE uses a special module of SE-

AGETIM (SE-AGETIM-BUILDING) that automatically generates the buildings with LODs, using a template definition that contains the LOD definition for any footprint shape.

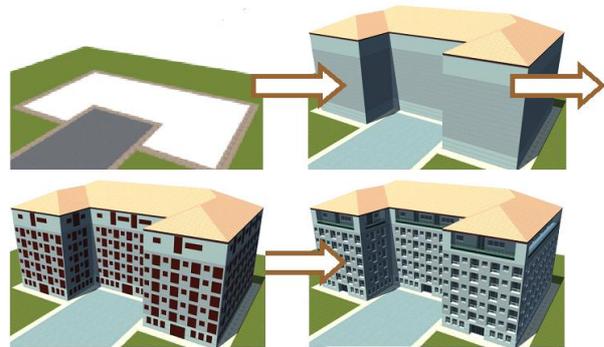


Figure 3. Generation of buildings using SE AGETIM BUILDING

Besides, the way a 3D object, as a building, is merged to the ground heavily conditions the amount of vertices on the terrain itself. The nominal way consists in integrating the object i.e. to add the building footprint vertices to the terrain mesh, which is very polygon consuming. The optimized way consists in superposing the 3D object on to the sloppy terrain. In that case, SE-AGETIM-BUILDING automatically creates a groundwork volume that interpenetrates the terrain without creating any polygon.

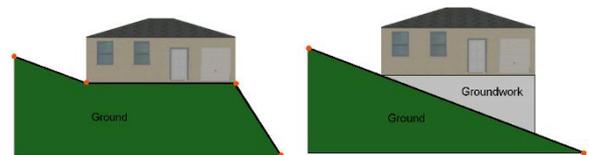


Figure 4. Creation of groundwork for a building

Texture constraints

The first constraint is due to the 3D graphic board and Open GL optimization. The worst situation for graphics is to change the material context for each polygon. The best way is to share the same graphic context for a lot of polygons. One important part of the material context is the texture itself. As a consequence, typically for objects, the idea is to put all the necessary image information in the same memory texture. This texture is called an "atlas". This is done automatically by SE-AGETIM-BUILDING, as illustrated here after, on the left the texture atlas, on the right the mapping on one building.

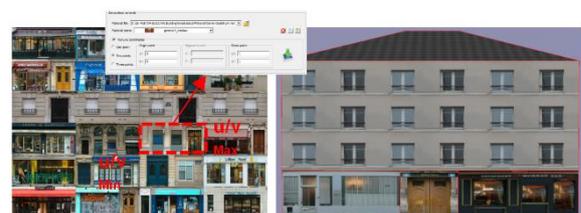


Figure 2. Use of a texture "atlas" for the mapping

Besides, for Infrared rendering in real-time, we use pixel shaders. A shader is a small piece of software, directly implemented on the graphic board in order to process the pixels in a user-defined way. Pixels shaders directly rely on the texture memory and no more on the RAM. SE-FAST-IR uses pixel shaders to simulate the black body law, to access to MODTRAN or MATISSE atmospheric tables ... The only constraint is to limit for one texture the amount of needed physical material. Beyond this limit, the real time performance collapses. OKTAL-SE products include specific tools that warranty that the limit is respected, which is fundamental for HWIL.

Database structure constraints

As already explained for textures, it is important to share the same graphic context for a lot of polygons. Typically in case of multi occurrences objects (for example 3D trees), it is better to group several trees into a same Open GL node, i.e. object. If not, for each tree object, a change of context is due, which is catastrophic for real time. On the opposite, gathering all the objects in the same super object is not a solution. Firstly, it is not good for Level Of Detail commutation and betweenning. Secondly, it is bad for "culling". The culling is the Open GL operation that consists in sending to the graphic pipe line only the polygons within the viewing frustum. OKTAL-SE tools perform a trade-off in between these two extreme strategies that provides the best real time performance.

3. PROJECTION MODE AND INJECTION MODE

The ideal situation for HWIL is the following: Everything is real (the missile, the IR seeker, the Image Processing algorithm). The only virtual components are the Image Generation and the movement platform. The Image Generation provides the scene perception by the IR seeker and the movement platform simulates the movement of the weapon system, for example a missile. In most of the cases, it is a closed loop simulation, which is very interesting to assess the IR seeker behavior and efficiency.

Two basic cases must be differentiated:

- First with the real IR camera in the loop, which is the most interesting case. It is called the "projection mode".



Figure 3. Projection mode

- Then, without the real IR camera in the loop. It is called the "injection mode":



Figure 4. Injection mode

In the "projection mode" the synthetic Image Generator sends radiance information through the DVI interface of the SE-FAST-IR PC platform, to an IR projector that emits photons that vibrate at the real infrared wavelength. Projectors are made of a matrix of micro bolometers that are commanded in temperature and emit all the more photons as the "pixel" is hotter. The well-known Mirage projector of Santa Barbara Inc is used by French and German governments for instance. In the new generation, these projectors can provide something like 1000 x 1000 pixels at some hundreds of HZ. In the "injection mode", the IR sensor is squeezed and replace by SE-IR-SENSOR simulation. In this case, the DVI output must be adapted to the weapon system private bus, by customer.

4. SE-FAST-HWIL validation

The core of the IG is based on SE-FAST-IR. Thanks to the Non-real-time and Real-time duality we focus the validation on the SE-RAY-IR, the ray tracing physical rendering and measure the difference in between SE-RAY-IR and SE-FAST-IR for exactly the same conditions.

The images below show an experimental validation of SE-RAY-IR by French DGA.



Figure 5. SE-RAY-IR validation

They show the way comparison is made between SE-RAY-IR and SE-FAST-IR. In this case, Black Body law gives the theoretical reference solution.

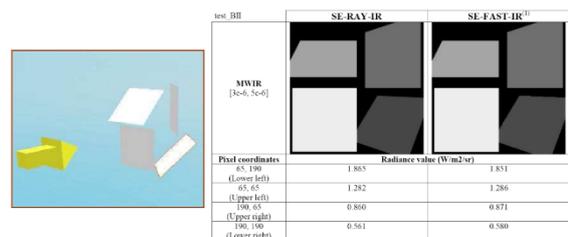


Figure 6. SE-RAY-IR / SE-FAST-IR comparison

5. SE-FAST-HWIL architecture and workflow

SE-TOOLKIT is the SE-WORKBENCH C/C++ API that is enhanced, in the frame of HWIL, by the SE-TK-D-SCNX API (for dynamic scenario edition) and by the SE-TK-FORM API (for interfacing to internal file formats).

SE-SPECIAL-EFFECT library allows to create efficient particle systems and to model flares and clouds.

Even if the Non Real Time tool: SE-RAY-IR is not part of this HWIL packaging, it is quite important, in order to assess the simplification made in the frame of SE-FAST-IR.

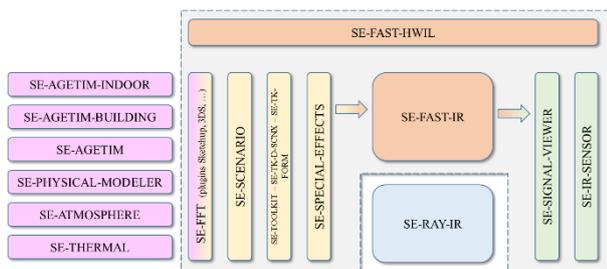


Figure 7. SE-FAST-HWIL architecture

Scenario edition

The initialization is made using SE-SCENARIO that delivers a scenario file. The scenario file contains the entities reference (objects and cameras) and the atmospheric and thermal data needed for infrared realistic representation. The dashed rectangle of figure 11 concerns the pre computations.

Data input

SE-FFT (File Format Transfer) product is a 3D geometric data converter, from and to the SDM format, inherent to SE-WORKBENCH tools. It handles meshed database (polygons characterized by textures, colors, etc.) used to describe terrains, objects and targets. Therefore, SE-FFT is an open product, whose use is necessary to import and export user data from and to SE-WORKBENCH tools.

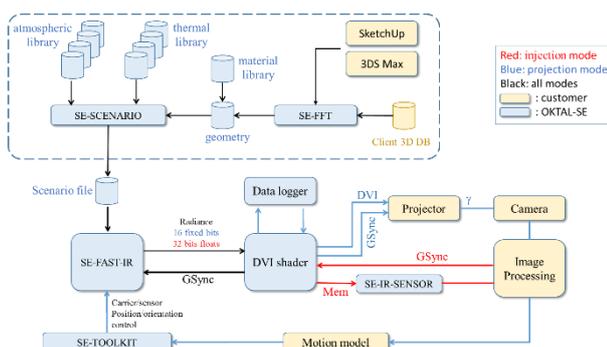


Figure 8. SE-FAST-HWIL architecture

SE-FFT enables the conversion from OpenFlight, OpenInventor, VRML, 3DS Max, SketchUp or TDF formats, towards the SDM format and vice versa (except for the TDF and SketchUp formats).

It also enables the conversion from the SDM format to the BSG format. BSG is a proprietary OKTAL-SE format that is optimized both for speeding files loading initialization duration and for improving real-time GPU performance. Therefore, SE-FFT interfaces applications at all exploitation levels of the SE-WORKBENCH tools. Indeed, SE-WORKBENCH tools all use the SDM format to describe the geometry of objects and their physical characterization in a coherent format. The SDM format is the open ASCII OKTAL-SE format of Synthetic Environment.

Moreover, most of those formats (OpenFlight, OpenInventor, VRML and 3DSMax) do not integrate the physical characterization of geometric data, necessary to their exploitation by SE-WORKBENCH tools. Therefore, SE-FFT enables to associate a physical characterization to the data during the conversion to SDM format.

3DS Max is a world class 3D modelling tool. SketchUp is a free modelling tool very simple to use. OKTAL-SE has developed special plug-ins within these tools. This enables the customer to modify the database.

Thanks to this plug-ins, the customer can modify the geometry of a given 3D database and attribute physical materials ready for infrared rendering thanks to a library of physical materials. This library of physical materials contains ready to use classified textured materials (such as wall of bricks, roof of tiles, asphalt ...) for most of the material one can find in a 3D scene.

6. SE-FAST-HWIL packaging

SE-FAST-HWIL package includes all necessary modules to set up customized applications:

- **SE-IR-SENSOR**, a module for simulation of infrared sensor effects
- **SE-FAST-HWIL CIGI interface**, that connects CIGI to SE-TOOLKIT
- **SE-HWIL-GRABBER**, that can store CIGI packets, to replay a given simulation with the exact same output
- **SE-HWIL-TRAJ**, that records and replay scripted trajectories
- **SE-HWIL-ENCODER**, a user-modifiable shader to adapt the format of the output images to a given IR projector
- **SE-HWIL-BENCH**, a package to benchmark user platform and estimate future performances (airport DB for HWIL, SEA DB for HWIL)
- A library of atmospheric files
- A library of thermal data files
- **SE-HWIL-METHODOLOGICAL_GUIDE**

6.1. SE-IR-SENSOR

SE-IR-SENSOR is a module of SE-WORKBENCH-EO allowing the simulation of generic IR sensor effects during image rendering process.

The purpose of the optronic sensor model implemented in the SE-IR-SENSOR tool is to model the real behaviour of an infrared sensor. The SE-IR-SENSOR library has been designed to be general enough in order to simulate a broad range of sensors, yet sufficiently detailed to be able to reproduce the effects of specific systems as accurately as possible. The Synthetic Image Generator (SIG) can be either SE-RAY-IR or SE-FAST-IR depending on the user needs. The user can choose between SE-RAY-IR model and SE-FAST-IR model:

- SE-RAY-IR model for accurate computation (non real time)
- SE-FAST-IR model for real time computation

The SE-IR-SENSOR library has the same common interface for SE-RAY-IR and SE-FAST-IR. The interface provides functionalities to transform input images produced by the SE-RAY-IR or SE-FAST-IR (in radiance level) into output grey levelled electric signal of the sensor (volts).

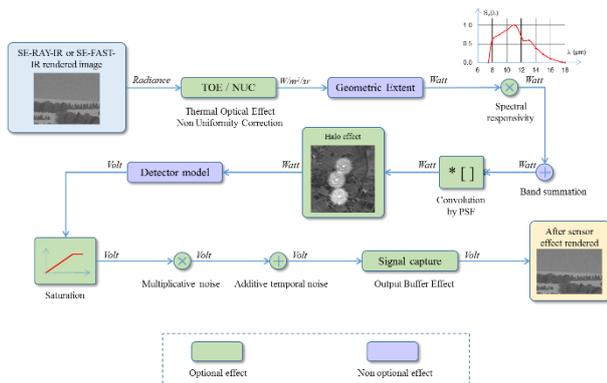


Figure 9. SE-IR-SENSOR architecture

6.2. SE-FAST-HWIL CIGI interface

SE-FAST-HWIL includes an interface to handle network messages from a host computer compliant with the CIGI standard. This interface allows a simulation host to control a set of Image Generators. A configuration file provides the ability to control the basic behaviour of the application components.

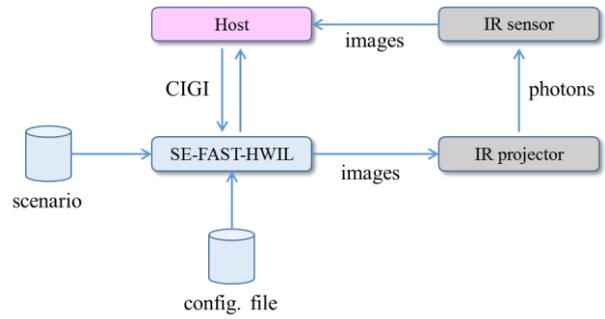


Figure 10. SE-FAST-HWIL CIGI interface

6.3. SE-HWIL-GRABBER

The basic need is to analyse a HWIL session and make an archive. For this requirement, OKTAL-SE proposes to rely on a very important feature of SE-Workbench: SE-Workbench-EO is completely deterministic. It means that if a simulation is played twice, exactly the same rendered images are generated. Indeed a scenario agenda in SE-SCENARIO gives a “frame by frame” very accurate scheduling of time (simulation time), including full animation control. Even the random like effects such as particles systems or SE-IR-SENSOR noises for injection mode rely on deterministic seeds.

The SE-HWIL-GRABBER can record the CIGI packets and store them in a file. For a replay of the simulation, SE-FAST-HWIL reads the CIGI packets previously stored in the file and replays the recorded CIGI commands with the exact same output.

These options permit the replay of a previous simulation, with exactly the same sequence of image. They emulate the behaviour of a video grabber, thus avoiding the cost of such hardware.

6.4. SE-HWIL-TRAJ

The SE-HWIL-TRAJ allows to store in a file, for each time step, the position and orientation of all objects and groups that have an associated script. This functionality is of primary importance when using positioning scripts (like floating models, oscillating effects or ground constraints), as they can be very slow due to telemetry requests to do.



6.5. SE-HWIL-ENCODER

SE-HWIL-ENCODER is a user-modifiable shader to adapt the format of the output images to a given IR projector.

Images generated by SE-FAST-HWIL are send through the video display interface to the display device (screen or IR projector). Most IR projectors have a display dynamic of 16 bits/pixel on only one channel, and display interfaces (like DVI or HDMI), provide 8 or at most 10 or 12 bits/pixel, for 3

channels (RGB). SE-HWIL-ENCODER defines the encoding to use 2 or 3 channels and obtain the required dynamic.

6.6. SE-HWIL-BENCH

Description

HWIL is a very tricky activity because it is very hardware dependent. In that frame, Image Generation is the bottleneck because every customer wants to simulate more and more complex 3D scenes, with more and more special effects, for more and more high frequency and accurate sensors. Actually, it is very difficult to assess the trade-off that is necessarily made between the PC hardware performance, and the database complexity.

In order to help the Client to assess this complexity, OKTAL-SE provides within the SE-FAST-HWIL package a set of 3D database that enables to prototype the expected performance for a given hardware and a given 3D database complexity.

The tests presented here after were performed on a PC with an Intel Core i7-4770K @ 3.50 GHz and a graphic board GeForce GTX TITAN Black with 6144 MB GDDR5 with "Antialiasing – Setting" set to: "8x CSAA".

1st database: basic bench

The basic bench corresponds to a combination of scripts that allow to generate a database with user defined parameters. This database is made of a grid of overlapping quadrangles. The user can tune the number of quadrangles and the percentage of overlapping. The quadrangles are mapped with an 8 materials texture.

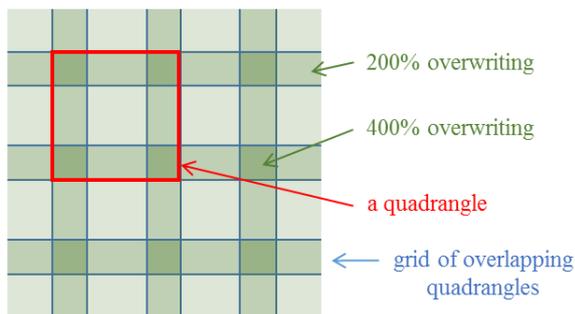


Figure 11. Basic bench

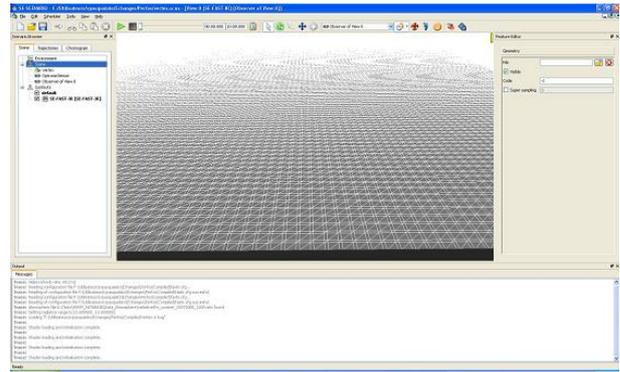


Figure 12. Basic bench in SE-SCENARIO

Results

Size of the images: 512 x 512

Polygon amount	Percentage of overlapping	Frame rate
500 000 triangles	0 % (no overlapping)	810 Hz
500 000 triangles	20 % of overlapping	590 Hz
1 216 800 triangles	0 % (no overlapping)	460 Hz
1 216 800 triangles	20 % of overlapping	290 Hz

2nd database: SE-AIRPORT database (HWIL version)

This test relies on the SE-ARIRPORT-DB 3D database that has been tailored to the needs of HWIL rendering. The database represents the Toulouse Blagnac airport, with a semi urban zone in the vicinity, and is assumed to be typical of an HWIL database. It is made of about 750 000 triangles, and 1.4 millions of vertices.



Figure 13. Airport database

The scenario context is band MWIR [3-5µm]. The atmospheric file is a MODTRAN based computation. The temperature are precomputed via SE-THERMAL. Two scenarios are available, one with a fixed point of view, with many object in the field of view, and one with the sensor moving along a trajectory, to show frame-rate variations.

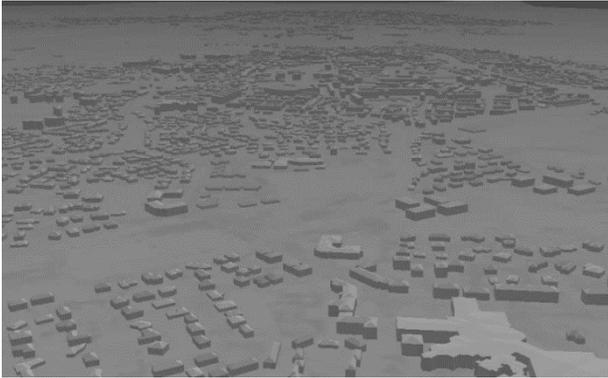


Figure 14. MWIR view in SE-SCENARIO

Results

1st test: The sensor set at a fixed position. The number of vertices seen in the field of view is 1 278 000 and the number of triangles is 639 700. Result: the frame rate is equal to 250 Hz.

2nd test: The sensor is set on a trajectory. Result: the frame rate varies between 230 Hz at the beginning of the trajectory, and 800 Hz at the end of the trajectory.

SE-SEA database (HWIL version)

This test relies on the SE- SEA -DB 3D database that has been tailored to the needs of HWIL rendering. The database represents the St Mandrier harbour in the South of France.

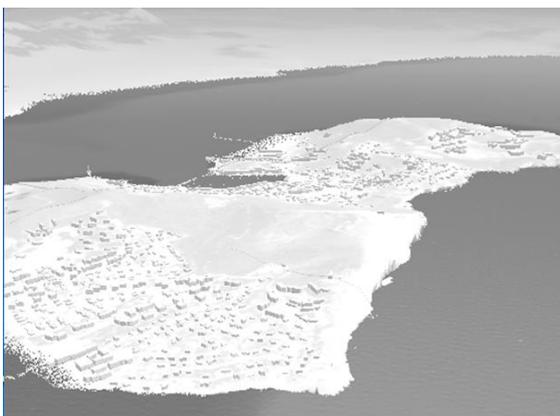
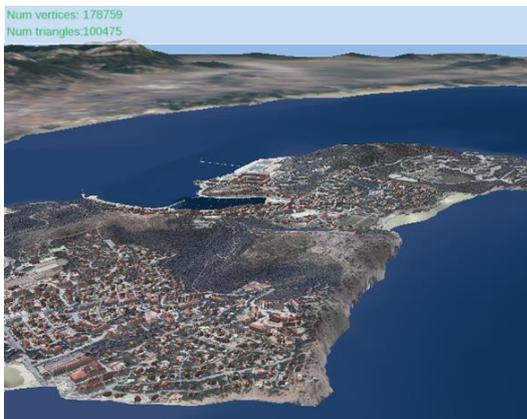


Figure 15. SE-SEA database

The sensor is set at a fixed location, the Field of View is 45°. The number of vertices seen in the field of view is 178 759 and the number of triangles is 100 475.

2 sizes of image have been tested: 512 x 512 and 1024 x 1024.

The tests have been performed for the 2 sea models:

- the "SINUS" model, where the SEA surface is modeled with a sum a 30 sine functions
- the "SWAN" model, where the SEA surface is modeled by an Inverse Fourier Transform of a wave distribution spectrum in the frequency domain (cf. [5])

Several functionalities and parameterization of the SE-IR-SENSOR model has been used in order to measure their impact on the frame rate.

Results

Image size 512 x 512

	"SINUS" model	"SWAN" model
without sensor effect	780 Hz	400 Hz
without additive noise	760 Hz	380 Hz
without multiplicative noise	760 Hz	380 Hz
without convolution 5 x 5	760 Hz	390 Hz
without convolution 15 x 15	760 Hz	360 Hz

Image size 1024 x 1024

	"SINUS" model	"SWAN" model
without sensor effect	360 Hz	320 Hz
without additive noise	325 Hz	300 Hz
without multiplicative noise	325 Hz	300 Hz
without convolution 5 x 5	340 Hz	310 Hz
without convolution 15 x 15	260 Hz	290 Hz

6.7. Atmospheric and thermal conditions

Concerning atmosphere, a set of pre computed atmospheric files are available. These files have been created using SE-ATMOSPHERE & MODTRAN5.

Several atmospheric conditions are delivered that cover all the crossed possibilities for summer or winter seasons, day or night, fine weather or bad weather, with or without fog, with or without rain.

The corresponding thermal data have been computed using SE-THERMAL and are also delivered.

6.8. Methodological guide

HWIL simulation has specific requirements compared to other types of simulations that can be difficult to achieve. This guide aims at helping SE-FAST-HWIL users to prepare and build their HWIL environment so that they can reach their goal with the less effort possible.

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