Application of a visualization environment for the mission performance evaluation of civilian UAS

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ABSTRACT

Future unmanned aerial vehicle applications require the development of new advanced design environments. In order to get an effective Unmanned Aerial System, UAS, solution it is necessary to take into account all elements of the system, e.g. to bring together aircraft design, payload, communication and other elements into one multidisciplinary design process. Compared to manned aircrafts, an Unmanned Aerial Vehicle, UAV, interacts with the environment through the onboard sensors. Therefore the sensor and communication performances as well as their implementation in the whole system play an important role for a mission fulfillment. An UAV design is then strongly driven by the mission, sensors and communication systems requirements. In the classic aircraft design approaches the sensor and communication performances are not part of the primary requirements and are taken into account on the operational analysis stage only, when the aircraft concept is already quite detailed. In order to take into account the sensor and communication requirements early enough an operational environment has to be simulated and implemented into the design loop.

KEYWORDS: *UAV, visualization, operational analysis, aircraft design, mission performance analysis*

NOMENCLATURE

ACR – area coverage rate
b – sensor ground swath width
d_c – object characteristic dimension
E – required energy for a mission
EACI - energy-rated area coverage index
f – degradation factor
FOV – field of view
f – focal length of the camera
GSD – ground sample distance
GSD_H – horizontal ground sample distance
GSD_V – vertical ground sample distance
h – vertical distance from the sensor installed on the UAV to the ground
H – height of the object
HFOV – horizontal field of view
Hpix – number of horizontal pixels of the camera
N – number of cycles across the target
P – distance between pixels of the camera
P() – probability of achieving target discrimination task
R – slant range
UA – unmanned aircraft
UAV – unmanned aerial vehicle
UAS – unmanned aerial system
V – flight velocity
VFOV – vertical field of view
Vpix - number of vertical pixels of the camera
W - width of the object
θ_{Look} – angle between the slant range and the sensor height over the ground

1 INTRODUCTION

Future unmanned aerial vehicle applications require the development of new advanced design environments. In order to get an effective UAS solution it is necessary to take into account all elements of the system, e.g. to bring together aircraft design, payload, communication and other elements into one multidisciplinary design process.
Compared to manned aircrafts, an UAV interacts with the environment through the onboard sensors. Therefore the sensor and communication performances as well as their implementation in the whole system play an important role for a mission fulfillment. An UAV design is then strongly driven by the mission, sensors and communication systems requirements. In the classic aircraft design approaches the sensor and communication performances are not part of the primary requirements and are taken into account on the operational analysis stage only, when the aircraft concept is already quite detailed. In order to take into account the sensor and communication requirements early enough an operational environment has to be simulated and implemented into the design loop. Therefore requirements for operational environment visualization tool are the following:

- High resolution texture data and elevation model based landscape;
- Aerial vehicle position and orientation control;
- Possibility to load and position additional 3D objects into the scenery;
- Collision control;
- Sensor control and geometry field of view representation;
- Communication line-of-sight geometry representation;
- Functional extension depending on a mission scenario and requirements.

In order to find the optimal configuration of an UAS for a specific mission and to enhance the performance of tasks a tool chain for mission simulation and evaluation is developed at the Institute of Aircraft Design, TUM. The visualization environment is part of the tool chain and allows to simulate the operational environment and the UAS carrying out a mission in it.
The paper is organized in the following way: the next section presents the state of the art of the visual simulation applications for the UAV design and assessment. In Section 3 the tool chain and the visualization environment are described. In order to verify the functional capabilities of the developed tool chain a sample mission of an aerial survey for vegetation analysis in agriculture is presented in Section 4. Section 5 contains the conclusion and further work.

2 STATE OF THE ART

For the mission simulation and evaluation of a UAS it is important to have a flexible tool, which can be tuned according to the requirements discussed in Section 1. With the rise of new technologies realistic scene visualization tools are in-demand for UAV flight performance evaluation and training applications. The most popular tools for aerial vehicle flight simulation and visualization are flight simulators such as Flight Gear, X-Plane and Microsoft Flight Simulator. Despite the fact that X-Plane and Microsoft Flight Simulator have a realistic environment representation and offer accurate aircraft models it is quite complicated to modify them according to the requirements described above. Flight Gear is an open source project and therefore modifications are possible. However the default installation does not provide the required realistic terrain data. It can be achieved by additional developments such as in [1]. A good description of possible usage of flight simulators for the UAS design and performance evaluation is presented in [2].
Quite often in research groups tools based on the high performance open source 3D toolkit OpenSceneGraph [3] are developed and used for visual simulation, virtual reality and scientific visualization, for example [4, 5].
After reviewing existing visualization tools, the osgVisual toolkit was chosen [6] as a basis for the development of the required visual operational environment for the mission simulation and evaluation tool chain. With high level visualization functions the software is used for scientific visualization and vehicle simulations. At the same time it can be easily extended or adapted to new needs by implementing additional OpenSceneGraph code.

3 MISSION SIMULATION AND EVALUATION TOOL CHAIN

3.1 Overview of the tool chain

At the current stage the tool chain (see "Fig.1") enables to simulate and visualize a civil ground surveillance and search and rescue missions with a precomputed flight route. The Simulation and Evaluation Tool consists of the mission management computer, the flight control system and the sensor visibility analysis block [7]. All initial air vehicle, mission and sensor data are stored in the data base model "Aircraft Design Data Model" ADDAM, which is part of the aircraft design environment "Aircraft Design Box" ADEBO, developed at the Institute of Aircraft Design, TUM [8]. The visualization environment continuously receives information about the UAV position and orientation, as well as the orientation of the EO/IR-sensor installed on the platform from the simulation model. The feedback data from the visualization environment are involved into the sensor performance and mission effectiveness evaluation process.

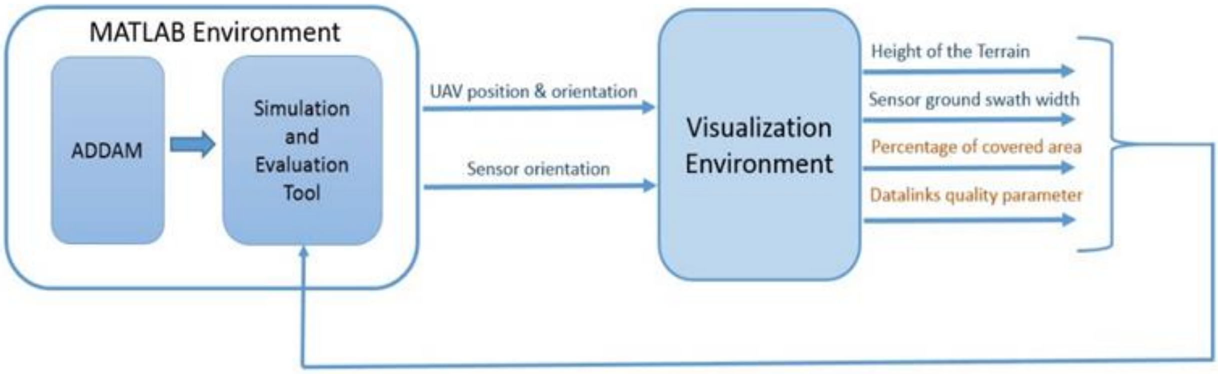

Figure 1: Structure of the mission simulation and evaluation tool chain

3.2 Rendering functionality of the Visualization Environment

The visualization part of the tool chain is based on the high-definition environment for spatial display of aircrafts osgVisualNG, which is the enhanced version of osgVisual. Both have been developed at the Institute of Flight System Dynamics, TUM. The terrain data is based on high resolution texture data and an elevation model based landscape. A more detailed description of osgVisual and osgVisualNG is presented in [6, 9, 10]. The osgVisualNG functionality includes:

- High resolution texture data and elevation model based landscape;
- Aerial vehicle position and orientation control;
- Possibility to load and position additional 3D objects into the scenery;
- Several camera view types;
- Module for creating overlays.

For the sensor and mission performance evaluation it has been upgraded with a set of new functions and options:

- Flight path representation;
- Sensor control, geometry field of view and ground sensor footprint representations;
- Area coverage representation on the terrain and it´s calculation;
- Communication line-of-sight geometry representation, obstacles detection, time of losses calculation;
- Objects of interest detection and calculation of a slant range distance to it.

The geometry representation of the objects in the scenery allows then to simulate the interaction of the UAS elements with each other and with the environment. The example of new rendering functionalities is presented in "Fig. 2".

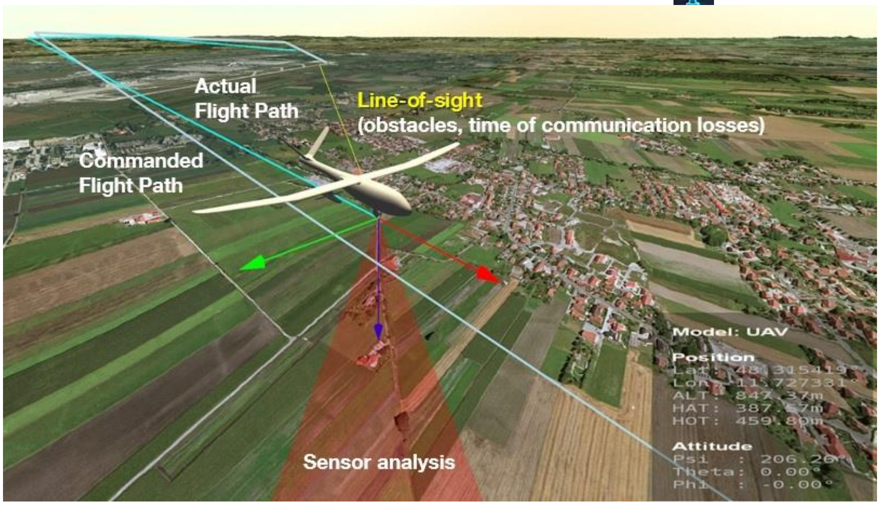

Figure 2: Rendering functionality of the visualization environment

The new rendering functionalities provide additional information for visual flight performance assessment, communication and sensor performance evaluation. The datalink quality assessment takes into consideration the following aspects: Communication range, obstacles in the line-of-sight and time of communication losses. Owing to the elevation model and realistic representation of the terrain the visualization software allows to model the communication range and to check for obscuration of the line-of-sight between the flying platform and the receiving station. These data can be included into the mission effectiveness evaluation. The sensor performance analysis plays a significant role in the mission evaluation process therefore it is considered separately in the next section.

3.3 Sensor performance analysis

In the current representation for the sensor performance analysis the sensor's field of view (FOV) is depicted by a pyramidal shape, where the base of the pyramid represents the footprint of the sensor on the ground ("Fig.3"). The size of the pyramid is determined by horizontal (HFOV) and vertical (VFOV) angles of the FOV of the sensor.

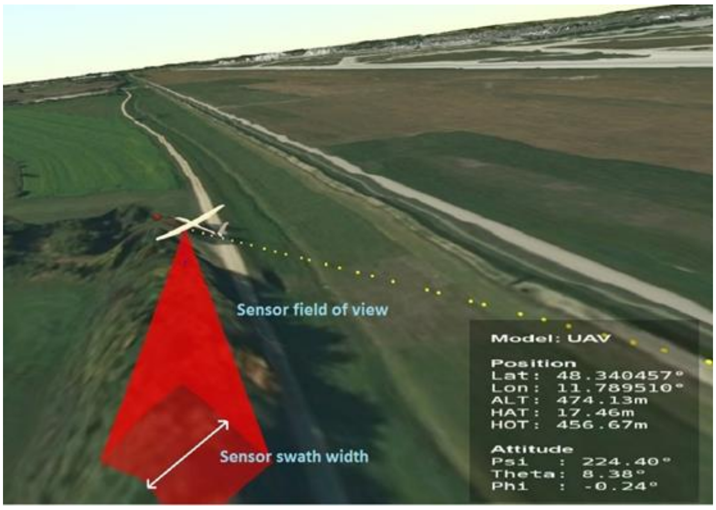

Figure 3: Representation of the sensor's field of view

Since OpenSceneGraph functionalities allow to detect intersection points between objects in the scenery, in this case between the pyramid and the terrain, the actual footprint area can be calculated in real time during the flight simulation. In order to get the area covered by the sensor for the simplified model the distance between two middle points on the base of the pyramid, i.e. the sensor swath width, is taken.
In the presented environment the following sensor FOV orientation modes can be simulated:

- The sensor is installed at a certain angle on the platform and the FOV change its orientation together with the UAV angular movements;
- The sensor is installed at a certain angle on the platform and the FOV stays stable during the UAV angular movements;
- The sensor is installed at a certain angle on the platform and during the flight the FOV is fixed on a certain point in the geospatial space.

The type of the remote sensing collection presented in the visualization environment is so called "push broom", where "the collection involves a swath of resolution cells which is roughly orthogonal to the flight path projected on the ground that are advanced via the UA forward motion" [11].
Depending on a mission task the trail on the ground as well as the pyramid can have one or more colors ("Fig.4"). For example in case of search and rescue type of missions it is important to know the pixel density on the ground. In order to give a better understanding of the sensor performance the color of the footprint or the FOV of the sensor in the visual operational environment can represent the pixel densities or the probability of target detection, respectively.
The sensor area coverage mapping shows the area covered by the sensor during the mission by marking the ground where the sensors FOV, i.e. pyramid, touches the terrain ("Fig.5"). It is possible not only to represent visually which areas have been observed, but to get the area of the region taking into account the terrain shape.

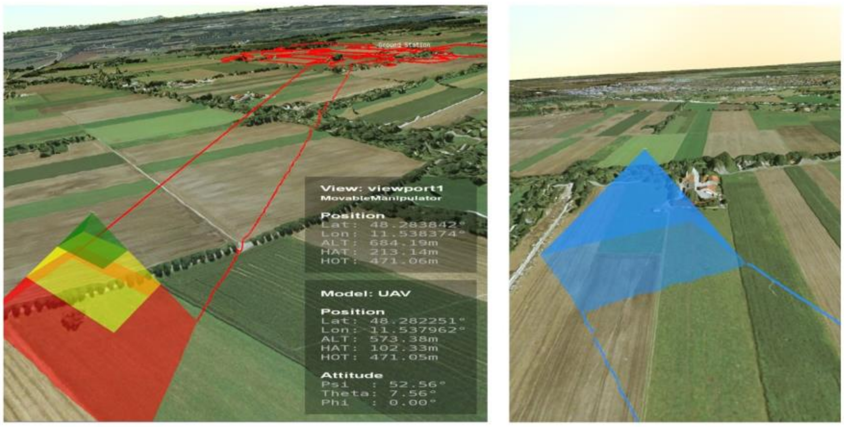

Figure 4: Color representation of the sensor's FOV and trail on the ground

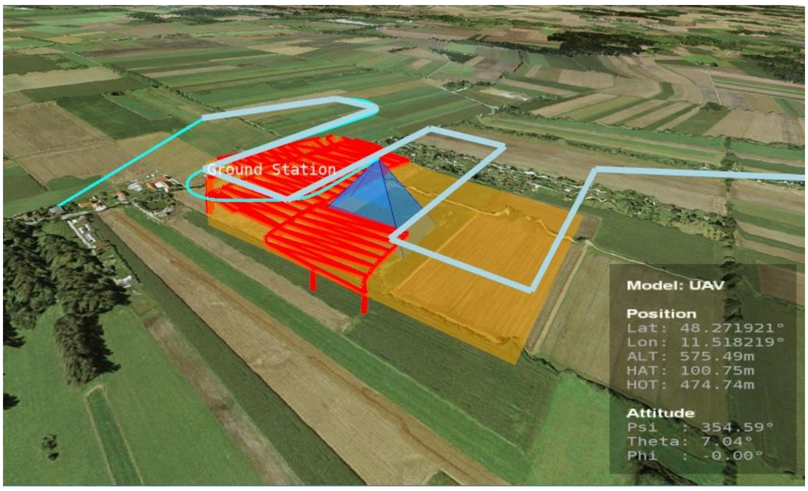

Figure 5: Area coverage mapping

The ray tracing approach allows to detect intersection points between the pyramid and the ground or the area of interest. Using the coordinates of the points a geometry representation of the sensor ground footprint is rendered and precisely located in the scenery. Therefore it is not necessary to calculate the sensor´s foot print location with separate algorithms. In "Fig. 5" the area of interest is colored with an orange color and the trail from the sensor with the red color.

3.4 Sensor performance evaluation

For the sensor performance evaluation it is important to know the sensor´s field of regard and the pixel density on the ground.
In the simplest case when the sensor is pointed vertically to the ground the sensor ground swath width b ("Fig. 3") can be derived from the field of view angle:

$$tan\left(\frac{FOV}{2}\right) = \frac{b}{2 \cdot h} \tag{1}$$

Where h is the vertical distance from the ground to the sensor. In the visualization environment this parameter is derived directly from the operational environment ("Fig. 6") by obtaining the coordinates of the two middle points on the base of the pyramid where it touches the ground and calculating then the distance between these points. In the regions where terrain heights are especially different, the sensor swath width derived by the presented approach would make significant difference compared to the sensor swath width on the flat terrain.

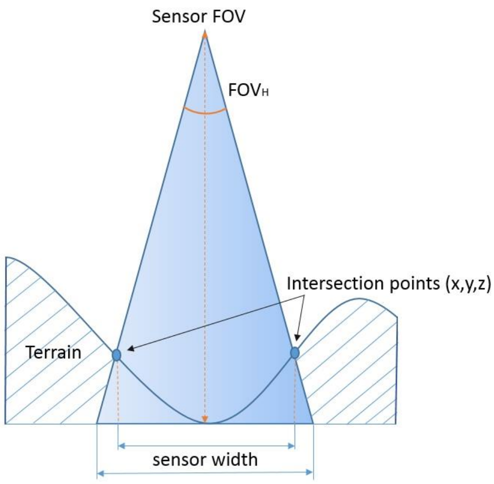

Figure 6: Sensor width calculation

In order to evaluate the possible quality of the gathered data by the sensor during the mission, the Ground Sample Distance (GSD) parameter and the metric based on the Johnson Probability Criteria [11] are introduced. According to Gundlach [11], the GSD parameter is a function of the focal length f of the camera objective and the optics geometry and in fact is "the distance between the pixels projected on the ground at slant range". The horizontal and vertical GSD parameter can be calculated then in the following way:

$$GSD_H = \frac{P}{f} \cdot R \tag{2}$$

$$GSD_V = \frac{P}{f \cdot cos\theta_{Look}} \cdot R \tag{3}$$

where P is the distance between pixels, the slant range R is the distance between the sensor installed on the UAV and the object of interest, θ_{Look} is the angle between the slant range and the sensor height over the ground.
Using the field of view angles of the sensor and its resolution, the equations can be rewritten as:

$$GSD_H = 2 \cdot tan\left(\frac{FOV_H}{2 \cdot H_{Pix}}\right) \cdot R \tag{4}$$

$$GSD_V = \frac{2 \cdot \tan(FOV_V/(2 \cdot V_{Pix}))}{\cos(\theta_{Look})} \cdot R \qquad (5)$$

where FOV_H and FOV_V are the horizontal and vertical fields of view respectively.
The Johnson Criteria [11] is a method based on the sensor´s resolution and it allows to calculate the probability P(N) of detection, recognition or initialization in the following way:

$$P(N) = \frac{(N/N_{50})^{2,7+0,7\cdot(N/N_{50})}}{1+(N/N_{50})^{2,7+0,7\cdot(N/N_{50})}} \qquad (6)$$

N_{50} denotes the number of cycles providing a 50% probability of a successfully detection task, where for detection N_{50}=0.75, for recognition N_{50}=3.0 and for identification N_{50}=6.0. N is a given number of cycles across the object of interest and is defined as an object characteristic dimension d_c divided by twice the GSD:

$$N = \frac{dc}{2 \cdot GSD} \qquad (7)$$

The object characteristic dimension is given by:

$$d_c = \sqrt{W \cdot H} \qquad (8)$$

where W is the width and H is the height of the object of interest.
The probabilities of detecting objects of interest are calculated during the mission simulation with the data derived from the simulated operational environment.
The area coverage rate ACR is an important parameter for the sensor performance metric. Taking into account the GSD the ACR is given by:

$$ACR = \int_0^T b(t) \cdot \mathrm{V(t)} \cdot \mathrm{f(GSD(t))dt} \qquad (9)$$

where f is the degradation factor [7] and is introduced in order to take into account allowed GSD limits, within which the gathered information is valuable.
A higher flight altitude leads to a bigger sensor coverage area. But at the same time with increasing the altitude, the GSD is dropping. Therefore in order to find a balance between the sensor coverage area, the quality of the gathered data and the energy required for the mission an Energy-rated Area Coverage Index EACI [7] is introduced:

$$EACI = \frac{ACR}{E} \qquad (10)$$

In that case the required energy for the mission E can be estimated by:

$$E = \int_0^T F(t) \cdot V(t) dt \qquad (11)$$

where F is the required thrust of the engine, V is the velocity of the UAV and T is the duration of the mission.

4 APPLICATIONS OF THE VISUALIZATION ENVIRONMENT

4.1 Aerial survey missions

In order to verify the functional capabilities of the developed tool chain a sample mission of an aerial survey for vegetation analysis in agriculture is simulated ("Fig.7"). The details of the mission are introduced in [7]. The goal of the mission is to gather information from two fields by the sensor. The fields are located in the north area from Munich and the distance between them is approximately 10 km. The area of the fields is around 10 ha. As platform the unmanned aerial demonstrator "IMPULLS", developed at the Institute of Aircraft Design, is used. The sensor installed on the platform has a resolution of 4000 x 3000 pixels and a HFOV = 73°.

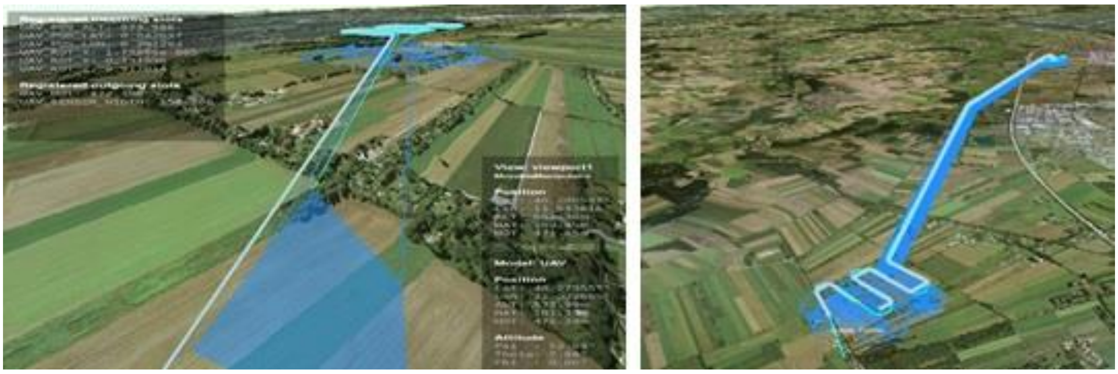

Figure 7: Aerial survey mission visualization

The flight path is calculated according to 24 predefined way points. The start and end points are located at the first field. The sensor camera is pointed vertically towards the ground. It is also possible to set the orientation angle of the sensor, change the flight path, altitude and to test other sensors in order to find the best mission, aircraft and sensor combination.

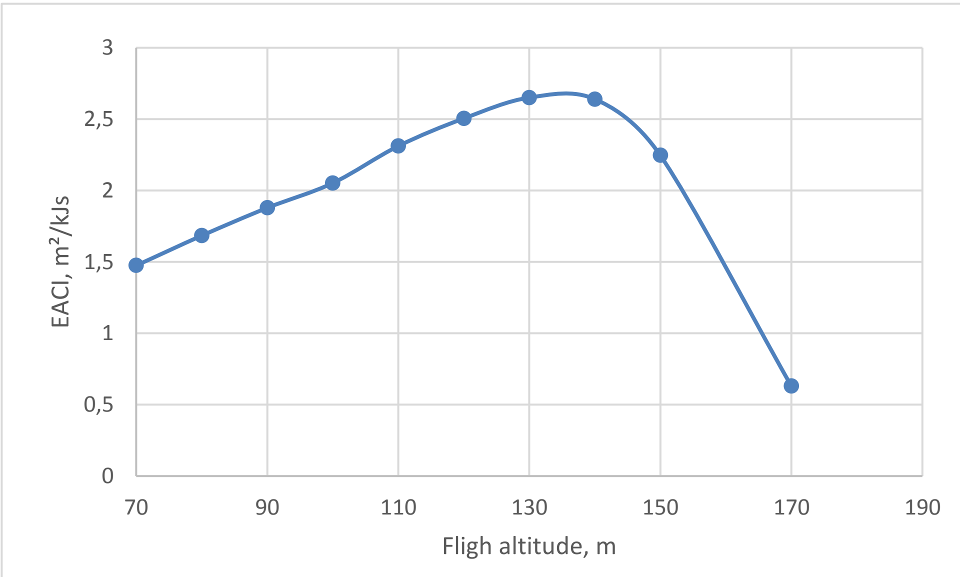

Figure 8: Results of the aerial survey mission simulation by varying the flight altitude

The results of the mission simulation are presented in "Fig.8", where the dependence of the energy-rated coverage area index, EACI, in relation to different flight altitudes is displayed. The higher the EACI, the bigger is the coverage area within the predefined GSD limits. Therefore the maximum coverage area with the required ground resolution can be achieved at the flight altitude 130-140 m. With the altitude more than 140 m over the ground, the quality of the gathered data is significantly reduced.
The similar results are presented in [7], which verify the data obtained from the simulated operational environment. The latter would have a particular meaning for missions in mountain areas or where the significant terrain elevation difference takes place.

4.2 Search and Rescue missions

The possibility to simulate search and rescue type of missions is introduced in the presented tool as well. For that type of missions it is especially important to obtain information as detection probabilities, number of detected objects, slant range distance to the objects and communication performance from the operational environment. A general example of the UAV accomplishing the search mission is presented in "Fig.8".

Figure 8: Objects of interest detection

In the visualization environment the approach for objects detection is based on geometry representation of the elements in the scenery and the ray tracing method. An object is counted to be possible detected when its geometry representation in the scenery will intersect the field of view of the sensor. The detection probability is calculated according to the Johnson Criteria [11] and is based on the slant range distance, which is calculated during the mission simulation as the distance between the sensor and the object of interest in the geospatial environment.

5 CONCLUSION AND FUTHER WORK

The presented tool chain allows to simulate and evaluate mission performance of the UAS. The visualization part simulates the operational environment and represents the results of the sensor performance, mission fulfillment and communication possibilities. This approach allows to take into consideration sensor and communication requirements within the UAV design loop. Based on the terrain shape the visualization environment provides the following information for the mission evaluation process and the UAS assessment:

- Sensor coverage area;
- Probability of objects detection;
- Number of detected objects;
- Slant range between the UAV and search objects;
- Communication range and obstacles detection in the line-of-sight;
- Time of communication losses;

In the presented tool search and survey type of missions can be simulated. The example of the agricultural aerial survey mission proves the reliability of the data obtained from the simulated operational environment. Moreover due to the visual representation of the coverage area it is possible to detect areas which have been not examined during the mission.

The flexibility of the tool chain allows to simulate and visualize different mission scenarios as well as different UAS configurations. It works in an accelerated mode as well as in real-time and therefore can be used for generating necessary statistical data for trade-off analysis. The next steps of the tool chain development are to introduce a complex mission performance index and to involve it into the aerial vehicle design process.

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