

UAV, sensor and mission matching approach using the visualization environment

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Advanced sensor technologies together with customer needs lead to a wider usage of Unmanned Aircraft Systems (UAS) or Remotely Piloted Aircraft Systems in civil, commercial, scientific and research missions. For most of these missions the goal is to gather information from the environment using sensors installed on the platform. The weight, size and power demand of the sensors are important parameters influencing the aircraft design as well as the mission performance. In order to evaluate tradeoff studies regarding the compatibility between the air vehicle, the sensor payload and the mission it is necessary to assess the system performance in a representation of the operational environment. This implies the use of enhanced mission simulation during UAS design. In this paper a method for unmanned air vehicle (UAV), sensor and mission matching issue based on the overall system assessment in the simulated operational is presented.

I. Nomenclature

ACR	=	area coverage rate
ACR_{ref}	=	referenced area coverage rate
a	=	weighting coefficient
β	=	weighting coefficient
CA	=	communication abilities
CA_{ref}	=	referenced communication abilities
γ	=	weighting coefficient
GSD	=	ground sample distance
dt	=	time step
E	=	required energy for the mission fulfillment
E_{ref}	=	referenced required energy for the mission fulfillment
f_{deg}	=	degradation factor
MPI	=	mission performance index
P_{det}	=	detection probability
$P_{det.ref}$	=	referenced detection probability
T_{cl}	=	time of communication losses
T, T_m	=	mission time
T_{ref}	=	referenced mission time
V	=	air speed of the vehicle
w_{swath}	=	sensor ground swath width
UAS	=	unmanned aerial system
UAV	=	unmanned aerial vehicle
UOI	=	user operating issues
UOI_{ref}	=	referenced user operating issues

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II. Introduction

The majority of current civil UAS applications deals with aerial survey or search and rescue tasks. For these types of missions key evaluation criteria are coverage area, image resolution and probability of target detection. The mission fulfillment grade depends on sensor parameters, flight altitude and speed, energy consumption and communication capabilities. Therefore, an UAS design is driven by aircraft, mission, sensor and communication systems requirements.

In order to take into account these requirements early enough, an operational environment has to be simulated and integrated into the design loop. Owing to the elevation model and realistic representation of the terrain, the visualization environment simulates the sensor payload performance and the physical world where the UAS is performing the mission. It provides the information concerning sensor coverage area, probabilities of object detection, number of detected objects, slant range between the UAV and search objects, communication range, obstacles detection in the line-of-sight and time of communication losses. These information are involved into the mission evaluation process and into the aircraft design loop of the tool chain developed at the Institute of Aircraft Design [1, 2]. Using this tool chain, an UAV can be optimized with regard of mission requirements already in the early stages of the design process. The next section presents the state of the art of the UAV, sensor and mission matching issue. The tool chain for the mission simulation and the sensor performance evaluation is described in section IV. Two UAS mission case studies i.e. aerial survey for vegetation analysis in agriculture and search and rescue mission, are presented in section V.

III. State of the art

The problem of matching sensor and UAV platforms to specific mission requirements has already been considered from different sides. The methodological approach presented by Preece et al. [3, 4] and Gomez et al. [5] solves the sensor-mission problem by means of collecting interlinked knowledge bases in form of ontologies, where the capabilities required by a mission are compared with sensors capabilities.

Another way is introduced at the Australian Centre for Field Robotics [6] where the visual representation of the mission simulation and the sensor capabilities are performed and used in order to find the best relation between the missions and onboard sensors.

At the Georgia Tech's Aerospace Systems Design Laboratory [7] an approach for aircraft concept selection and evaluation based on creating the inclusive overall evaluation criteria is presented. In this approach aspects such as affordability, mission capability, operational safety, operational readiness and survivability are considered. These aspects are also taken into account in the approach presented by Morawietz [8]. The last one is based on the House of Quality method and is called House of Metrics. In this approach "the method for supporting a holistic evaluation process through the derivation of a descriptive metric structure in combination with relevant decision parameters is presented" [8].

The research goal presented in this paper is to involve the sensor performance into the air vehicle design process, to assess the system effectiveness in terms of civil and commercial UAS applications and by this to evaluate tradeoff studies regarding the compatibility between the air vehicle, its sensor payload and mission requirements. Compared to the methods described above, the approach presented in this paper is based on the enhanced mission simulation and evaluation of the UAS in the visualized operational environment. This allows in addition to the classical mission performance criteria to evaluate the sensor performance during the mission simulation and to include it into the overall mission performance index. Including the mission simulation process into the multidisciplinary UAS design methodology allows to tailor the design specifically to predefined mission requirements.

IV. Mission and sensor performance simulation

The mission simulation and evaluation tool chain is able to perform different UAS mission scenarios. It consists of UAS design, simulation and evaluation, visualized operational environment and optimization parts. The overall structure of the tool chain is presented in Fig.1. The UAS design environment creates a feasible design according to mission requirements.

The simulation part consists of the Mission Management Model, the Flight Control Model and the Sensor and Mission Performance Analysis block. The Mission Management Model is a central element of the simulation model. It generates waypoint navigation commands, distributes input data for other model elements and sends flight state information to the sensor model. After performing the simulation it stores the results into the data base for further evaluation. The aircraft's current position, velocity and attitude angles are calculated using linearized equations of

motions in the Flight Control Model block. In the Sensor and Mission Performance Analysis block sensor results are calculated according to the mission type [9].

The visualization environment continuously receives information about the UAV position and orientation, as well as the orientation of the sensor installed on the platform from the simulation model. The feedback data from the visualization environment is used in the sensor performance and mission effectiveness evaluation process. As output a scalar value called Mission Performance Index (MPI) is obtained, which allows to assess and compare different UAS architectures. The MPI is then used as objective function in the optimization process [10]. By systematically varying initial wing geometry and sensor types multiple designs are created and evaluated. From randomized values of design variables a finite number of UAS configurations is generated, evaluated by the ability to fulfill the mission and ranked by the MPI. Afterwards a new “generation of children” by using methods of randomized recombination, mutation and saving best individuals of “parents” are created. This process is repeated until no further improvements of the MPI is achieved [9].

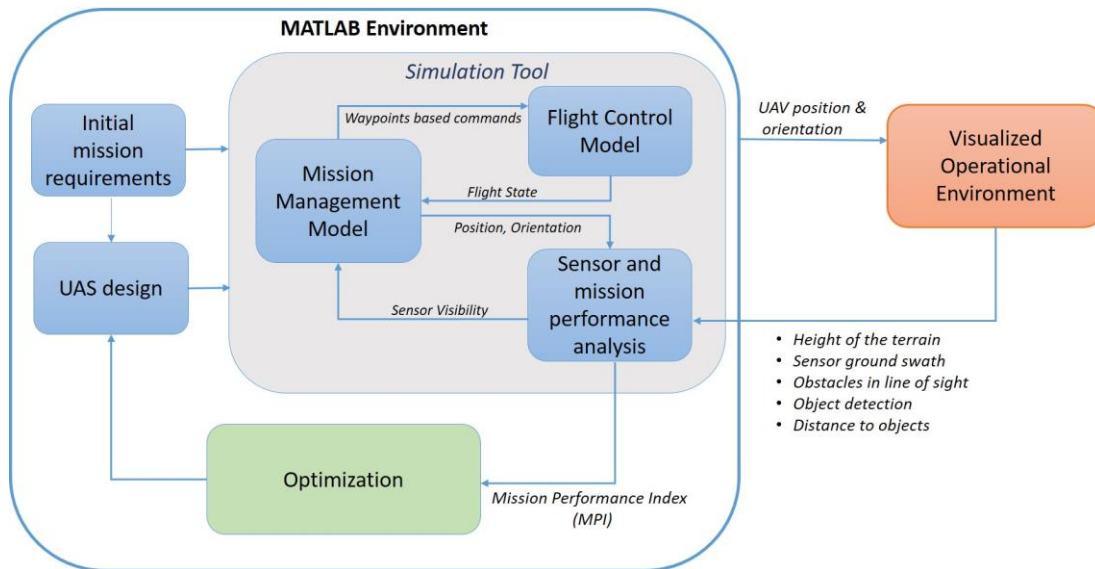


Fig. 1 Structure of the mission simulation and evaluation tool chain.

A. Visualization of the operational environment

By simulating the visual operational environment it is possible to take sensor and communication requirements into account in the UAS design process. Owing to high resolution texture data, elevation model based landscape, simulation of interaction of the UAS elements with each other and the environment the following information for the evaluation process of the UAV, sensor and mission matching is obtained:

- 1) Sensor ground swath
- 2) Detection probability of search objects
- 3) Slant range between UAV and search objects
- 4) Communication range and obstacles detection in the line of sight
- 5) Time of communication losses
- 6) Height of the terrain

For the mission types such as surveillance and search and rescue (SAR) it is important to cover a certain area of interest with desired image quality and to detect objects of interest in a limited amount of time. Examples of such missions are search of avalanche victims in mountainous areas, species monitoring, forest and fire monitoring and agricultural applications [11].

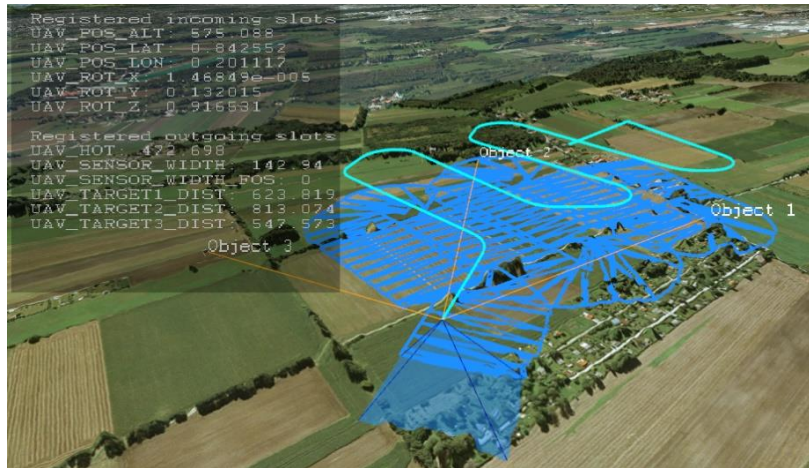


Fig. 2 Case study: Aerial survey for vegetation analysis in agriculture.

A general example of an UAV accomplishing a mission in the visualized operational environment is presented in Fig. 2 and Fig. 3. The field of view of the camera sensor is depicted by a pyramid shape, which is determined by the horizontal and vertical angles of the sensor's field of view. Owing to the terrain shape the actual sensor ground swath is calculated during the simulation. The mapping of the coverage area allows to visually detect areas, which have been not examined during the mission simulation [1].

The sensor is installed on the platform at a certain angle. The field of view of the sensor can change its orientation together with the UAV angular movements or stays stable pointing towards the ground. Figure 3 presents these two different sensor orientation modes. During the mission simulation and visualization one can see that the first mode gives bigger coverage area at the turns and therefore the possibility to detect objects.

In order to assess sensor performance for SAR type of missions, locations of object of interest are defined. This is realized by generating random location points within a certain area or by defining in the initial settings. With these coordinates the objects are placed in the virtual operational environment. The visualization environment allows to detect intersections between the objects in the scenery by means of ray tracing method. Therefore by using geometric representation of the UAS elements in the scenery it is possible to detect exactly when the search objects will occur in the field of view of the sensor. The detection probability is based on the slant range distance between the sensor and the object and is then calculated according the Johnson Criteria [12]. Therefore, it is possible to simulate and evaluate the probability that the search objects will be detected by an operator.



Fig. 3 Sensor field of view orientation modes

B. Mission performance index

In order to assess different UAS systems architectures a mission performance index is introduced. It takes into account different mission performance contributing factors and is represented as a sum of weighted and normalized key mission performance parameters. Equation (1) shows the general form of the MPI using a weighted sum approach [9]:

$$MPI = \sum_i \alpha_i \cdot \frac{Effectivity_i \cdot Degradation_i}{Effectivity_{ref,i}} + \sum_j \beta_j \cdot \frac{Effort_{ref,j}}{Effort_j} \quad (1)$$

The contributing parameters are divided into 3 groups:

- 1) Effectivity parameters positively influencing the mission performance, such as area coverage rate, number of detected objects.
- 2) Effort parameters quantifying resources needed to fulfill the mission, such as mission time, fuel.
- 3) Degradation factors reducing mission success, such as reduced ground sample distance, obstacles in the line of sight.

Each factor is normalized to its reference value and weighted according to its importance. All weighting factors have to sum to unity.

According to the presented possibilities of the mission simulation and evaluation tool chain, the MPI is defined as:

$$MPI = \alpha \cdot \frac{ACR}{ACR_{ref}} \cdot f_{deg}(GSD) + \beta \cdot \frac{E_{ref}}{E} + \gamma \cdot \frac{P_{det}}{P_{det,ref}} + \delta \cdot \frac{T_m}{T_{m,ref}} + \varepsilon \cdot \frac{CA}{CA_{ref}} + \zeta \cdot \frac{UOI}{UOI_{ref}} \quad (2)$$

The effectivity area coverage rate (ACR) parameter is defined as covered area per mission time T:

$$ACR = \frac{1}{T} \int_0^T w_{swath} \cdot V dt \quad (3)$$

where w_{swath} is the ground sensor swath width and V is the airspeed during the mission.

In order to take into account limits of the GSD a degradation factor $f_{deg}(GSD)$ in form of an exponential function is introduced [2].

The energy consumption effort parameter E is introduced in the metric separately from the ACR. The reason of that is the possibility to give it a separate weight for those type of missions where the energy factor is quite important.

The probability of object detection P_{det} is calculated according to the Johnson Criteria [12, 13] and the object detection time [9]. The dependence of detection probability and detection time is presented in Fig. 4. It is based on the data that an average a human needs 0,25s to just notice visual changes [14]. It is assumed that an operator needs minimum 2 second to notice an object and to give a value to it. The probability of detection at that moment would be considered as 70%. With increased time the detection probability is linearly rising and achieves 100% at a time of 10s.

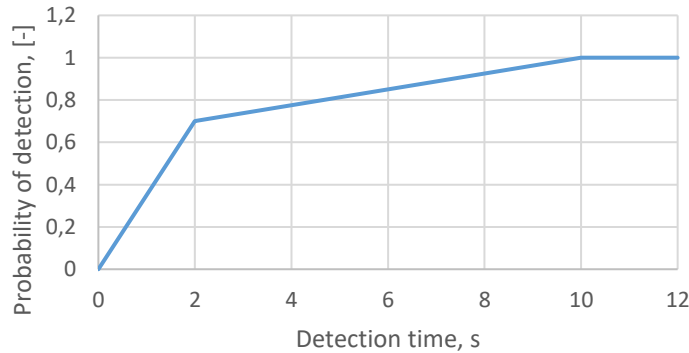


Fig. 4 Dependence of detection probability and detection time

The Communication Abilities (CA) parameter gives information about time of communication losses T_{cl} and the possibility to store data on board during the losses. The next step is to include in this parameter information about bandwidth limit and data transmission rate restrictions.

$$CA = \frac{T_{mission} - T_{cl}}{T_{mission}} \quad (4)$$

UOI stands for User Operating Issues. It is represented in form of a scalar value within the range from 0 to 1 and can contain information about launch/landing options according to the system weight, how easy is it to use the system, if it needs any special handling or storage facilities and how environmental sensitive the systems is. For example, the most attractive UAS for an agriculture application would be robust, hand-launched and belly-landed, not sensitive to environment conditions and of course easy to operate.

A complicated part of the MPI definition is the assignment of the weighting coefficients $\alpha, \beta, \gamma, \delta$. Despite the fact that there are many methods for weight assignment, this process still stays subjective and has to be adjusted to every mission case by the design engineer based on engineering insight and experience.

V. Mission design case and results

The objective of the presented design study is to evaluate tradeoff between mission, UAV configurations and sensor camera installed on the platform using the tool chain and metric presented above. In the optimization process wing area, aspect ratio, flight speed and camera type are used as design variables. As a basic configuration a conventional fixed-wing with V-tail is chosen. The objective function of the optimization is to maximize the MPI.

A. Agriculture survey mission design case

With population growth agriculture has to become more productive. Using UAS land management practices can be improved, yields increased and costs reduced. Therefore agriculture may become one of the most demanding applications of UAS [15]. For agriculture applications UAS have to be robust, simple to use and inexpensive. Runway-independent fixed-wing or VTOL systems have an advantage because they can be operated directly from fields or close to it. Depending on the mass the UAS can be hand-launched and belly-landed and therefore special launch equipment do not have to be provided.

Mission description and possible UAS configurations

A farm field with size of 4 km² north of Munich (Germany) has to be observed. Take-off and landing are performed near to the field. In Table 1 the UAS design variables and their ranges are specified. The possible camera types which are used in the design case as payload are presented in Table 2. Depending on the size, weight and resolution the cameras belong to different classes.

Table 1 UAS design variables

Design variables	Min	Max	Unit
Wing area	0,1	1,5	[m ²]
Aspect ratio	5	15	[-]
Design speed	10	15	[m/s]
Camera index	1	3	[-]

Table 2 Camera types used for optimization

	Camera 1	Camera 2	Camera 2
Sensor resolution	1920x1080	5456x3632	11608x8708
Focal length	24mm	24mm	24mm
Field of view	53°	53°	51.8°
Weight	0.1 kg	0.42 kg	1.53 kg
Index in the tool	1	2	3

The desired image quality and flight altitude are defined by the required GSD, in this case 5 cm. In agriculture UAS mostly operate at an altitude below 120 m above ground level [15]. However according to German Federal Law [16] the maximum allowed flight altitude is 100 m. All altitudes higher than that require a special permission.

In the case of agriculture missions the most important criteria are area coverage rate and energy consumption. Their importance for the presented design study is assumed equal and therefore the weighting coefficients are taken as $\alpha= 0.5$, $\beta=0.5$. Communications losses do not occur during the simulation and UOI criterion is not taken into account:

$$MPI = \alpha \cdot \frac{ACR}{ACR_{ref}} \cdot fdeg(GSD) + \beta \cdot \frac{E_{ref}}{E} \quad (5)$$

Modelling and results

The optimization defined an optimum UAS configuration according to the mission requirements. The progress of the MPI and design variables during the optimization is presented in Fig. 5 and Fig. 6 respectively. The designed UAV has a 1.04 m² wing area, 12.06 aspect ratio and 4.43 kg of total weight. The mission is fulfilled in almost 3 hours, with the flight speed 12 m/s at the maximum possible altitude of 100m. With the lightest camera type and with the smallest resolution 1920 x 1080 the desired image quality of GSD 5 cm is achieved.

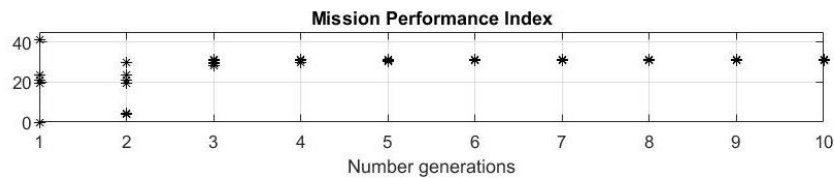


Fig.5 Mission performance index variation during optimization

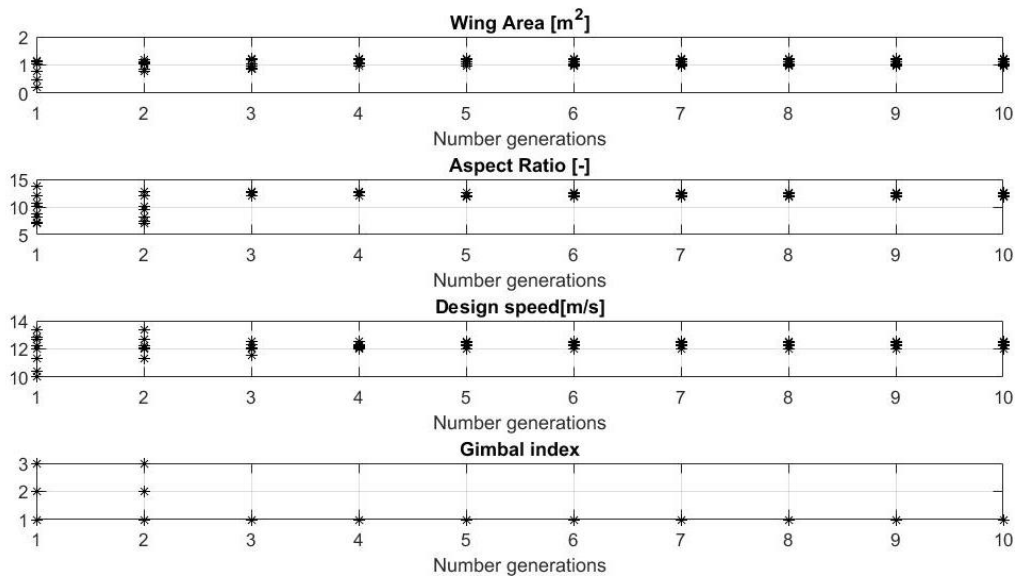


Fig.6 Variation of design variable values during optimization

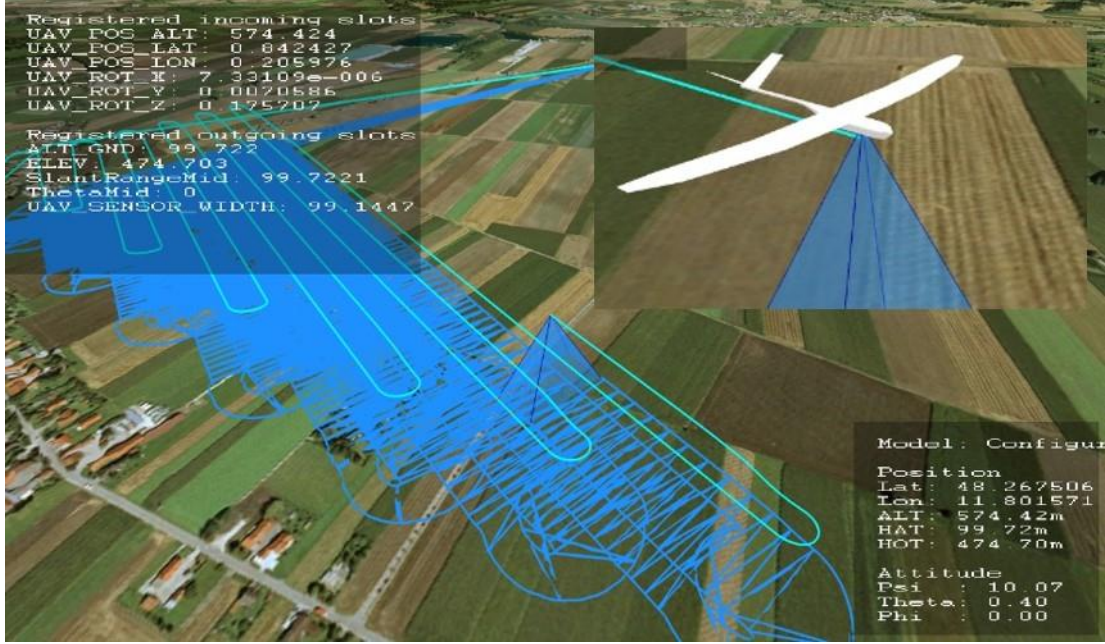


Fig.7 Agriculture mission simulation in the visualization environment

B. Search and rescue mission design case

Search and rescue UAS application is taken as a second design case presented in this paper. According to Gundlach [15] “UAS can improve response time and provide enhanced coverage”, therefore it can be useful in many cases of emergency response applications, such as SAR, communications relay, cargo delivery and security.

The most important evaluation criteria for SAR missions are objects detection time and time needed to cover the search area. Other criteria get second and third priorities and at the moment for simplicity are not taken into account. Therefore, for n search objects or locations the MPI is introduced in the following way:

$$MPI = \gamma \cdot \frac{\frac{\sum_i^n P_{det}}{n}}{\left(\frac{\sum_i^n P_{det}}{n}\right)_{ref}} + \delta \cdot \frac{T_m}{T_{m ref}} \quad (6)$$

where P_{det} is the objects detection probability and T_m is the mission time.

It is assumed, that finding the search objects is more important than the whole mission search time, therefore weighting coefficients are taken as $\gamma=0.7$ and $\delta=0.3$. With the detection probability of 70% the boat is considered to be detected.

Mission description and possible UAS configurations

The objective of this mission is to detect a missing boat within the shortest time at three possible locations, determined at the beginning of the simulation. These three different spots are defined in order to take into account the uncertainty of the boat location. For the simulation purpose the boat is defined as a cube with the size of $2.7 \times 2.7 \times 2.7$ m³. The search area is about 10 km² and is located on the Lake Constance close to Langenargen.

The design variables and their ranges are presented in Table 3. The camera types which are used in the optimization are presented in Table 4. According to the German Federal Law [16] the maximum allowed flight altitude is 100 m. However, because of a search and rescue type of mission it is assumed that there is no limitation for the altitude and it is determined by the required GSD and the camera resolution. In order to not only detect the boat on the water, but to recognize it the GSD has to be smaller than 40 cm. This can be achieved either by lower flight altitudes with lighter sensors and smaller resolution or by bigger sensors with higher resolution at higher altitudes.

Table 3 Design variables for the SAR design case

Design variables	Min	Max	Unit
Wing area	0,2	3	[m ²]
Aspect ratio	5	15	[-]
Design speed	15	40	[m/s]
Camera index	1	3	[-]

Table 4 Camera types used for optimization

	Camera 1	Camera 2	Camera 3	Camera 4
Sensor resolution	1920 x 1080	1280 x 720	1280 x 720	1920 x 1080
Max Horizontal Field of view	59°	31.5°	30°	31.2°
Weight	1,2 kg	4 kg	6.8 kg	16.8 kg
Index in the tool	1	2	3	4

Modelling and results

The results of the optimization process presented in Fig. 8, Fig. 9 and Fig.10 show that with camera 1 or camera 2 the boat was detected and recognized in all three possible positions during the mission. With camera 1, the flight speed of 24 m/s and at the altitude of 600m the search area is covered in 28 min. With camera 2, the flight speed of 19 m/s and at the altitude 800m over the water level the whole search area is covered in 34 min.

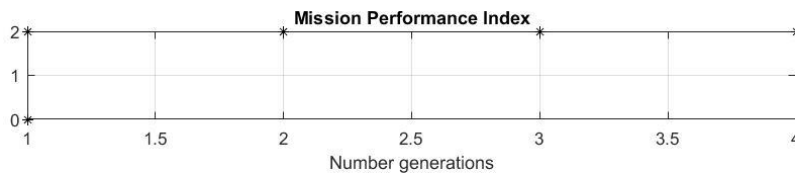


Fig.8 Mission performance index variation during optimization

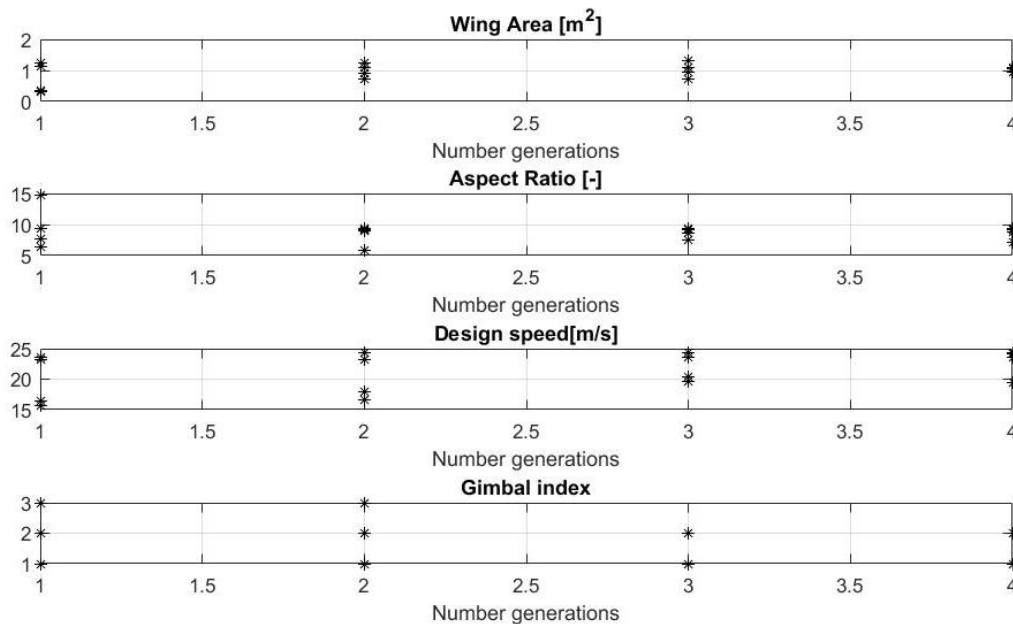


Fig.9 Variation of design variable values during optimization

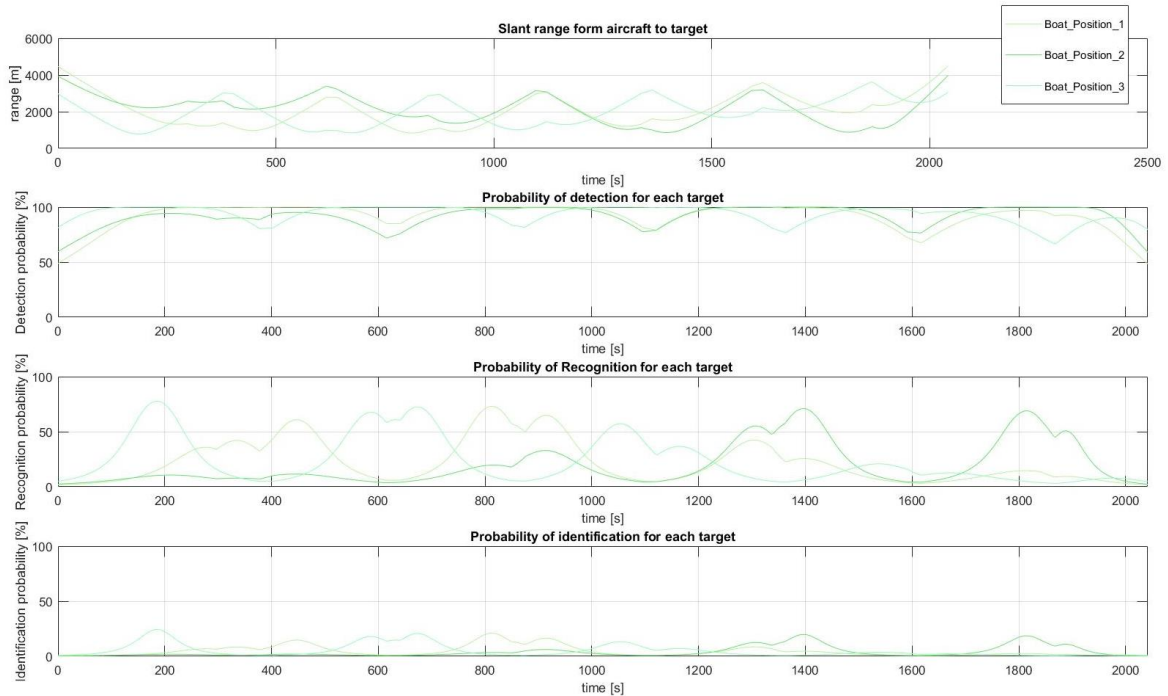


Fig.10 Results of the SAR mission simulation

VI. Conclusion

The presented mission simulation and evaluation tool chain allows to evaluate tradeoff studies regarding the air vehicle, the sensor payload and the mission matching problem.

The visualization part of the tool chain allows to assess sensor performance and communication capabilities in the simulated operational environment and to use the derived information in the UAS design process. In order to compare different UAS architectures and their mission effectiveness the evaluation metric based on the MPI is introduced. The combination of the UAS design process, performance evaluation metric and the optimization algorithms allows to generate a UAS architecture tailored to the mission requirements.

The final metric representation is still an ongoing research topic, where the most critical part is the weighting assignment. The background for communication analysis is implemented into the tools, but it did not take part in the presented design studies. These and a complex mission design case study presentation are the next steps in the research process.

The presented tools are flexible and modification are possible, therefore new algorithms such as trajectory path optimization, improved objects detection algorithms and others can be implemented.

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