Automated Low Altitude Air Delivery

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Abstract

This paper provides an overview of a recent project of DLR that conceptually considers unmanned air cargo delivery. Flying at very low altitudes to avoid other air traffic and limiting the flight route to low risk areas shall enable a mitigation approach based on the specific operation risks. For this operation centric approach, many different aspects including aircraft design, flight guidance, on-board hard- and software design, and risk assessment are investigated for payloads in the range of one ton. The paper outlines the scheme of the project, expected outcomes and validation approach.

1. INTRODUCTION

Automated cargo delivery is one of the civil applications for unmanned aircraft (UA) that is often considered to play a significant role for aviation in the future. A new project of the DLR (German Aerospace Center) called *Automated Low Altitude Delivery (ALAADy)* investigates the application of a very low level flight unmanned aircraft for an innovative approach of cargo delivery. Below common air traffic, payloads of around 1 t are carried. This project investigates new safety concepts and the economical validity of this class of unmanned cargo aircraft (UCA). The aim of this paper is to give an overview on this new project and its goals.

Unmanned cargo aircraft have received increasing attention in recent years. Small UCA in the range of a few kilograms of payload, are the focus of ongoing research and development that is already achieving high technology readiness levels (TRL). Examples are projects currently present in different media including the DHL Parcelcopter, Amazon Prime Air and Google's Project Wing. Smaller companies also edging into the market, for example Matternet, California, which focus on humanitarian applications.

In general, bigger scale systems are currently limited to lower TRLs. One exception is the optionally piloted Lockheed Martin K-Max, see [16] as an early reference. Other UCA related projects, such as Wings for Aid [21] in the Netherlands or a military application of the DARPA (Defense Advanced Research Projects Agency) financed project ARES (Aerial Reconfigurable Embedded System [1]) work with lower TRLs.

A significant amount of research has been performed for larger scale UCA. The question of whether UCA will be accepted by society is part of [15] and is an early example. It was found that acceptance, especially for UCA, is possible if sufficient information is provided.

Airspace integration for high flying UCA was addressed e.g. in [7, 8, 20]. Airspace integration of low flying drones is currently considered in the NASA Unmanned Aerial System Traffic Management (UTM) project, cf. [13]. Here, concepts are designed and realized that enable information distribution about flight corridors for low flying unmanned aircraft.

In the last decade, the need for regulation of civilian unmanned aircraft systems became imminent. Although the adaption of the original military technology seemed to open a lot of civilian business cases instantly, especially bigger aircraft systems above 150 kg were lacking suitable certification bases for design. Today, this lack is still present for civilian applications. Approval and construction regulations will need to be established by legislature in the future, so that newly developed unmanned aircraft systems can be certified and approved.

Standardization bodies like EuroCAE (European Organisation for Civil Aviation Equipment), RTCA (Radio Technical Commission for Aeronautics) early addressed these topics. The effort resulted in requirements and first proposals for certification specifications, e.g. CS-LURS (Light Unmanned Rotorcraft Systems) published by JARUS (Joint Authorities for Rulemaking on Unmanned Systems) [12]. However, design of an aircraft can only begin, if the safety target has been defined. This missing ingredient of defined safety targets could be covered by the 2nd issue of JARUS AMC-1309 [11], which basically puts the safety target of catastrophic failures for highly automated vehicles at 10^{-7} per flight hour.

EASA (European Aviation Safety Agency) has published a new concept of operations for drones in March 2015 [3]. This document basically deals with the regulatory problem, by introducing new risk-based categories allowing to define specific application tailored safety requirements. EASA now considers three different classes for UA, the open, specific and certified category. The major paradigm change in this approach is that the crash or accident of the aircraft is no longer considered to be a hazard to be prevented. In lieu, there are only three safety risks to be addressed: mid-air collision with manned aircraft, harm to people and damage to property.

This paradigm is the fundamental prerequisite for the idea of the ALAADy concept, since by flying low and potentially applying a traffic management system like UTM, the first safety risk can be addressed. Harm to people and infrastructure is usually location dependent. Thus, either an unmanned cargo aircraft is designed to meet thorough airworthiness requirements making it very unlikely to crash, or alternatively the operation is restricted to areas with reduced ground risk. The first method is mirrored by the EASA certified category [4, 5].

The second methodology is enabled by the introduction of the specific category, which facilitates the use of a specific operation risk assessment (SORA). A similar methodology is already being applied by the Switzerland Federal Office of Civil Aviation [6], which is limited to a gross weight of 150 kg. Interestingly, there is no implicit weight restriction for the EASA specific category yet, although there is conflicting information from the official documents, that one might possibly be imposed. For the scope of the ALAADy project, we assume that the targeted aircraft size could be operated in the yet to be completely defined specific category.

Simplified, this approach bridges the gap to safely operate a system of lower reliability compared to manned aviation and enables a change in design methodology. While in manned aviation, target failure rates are provided for a certain class of aircraft independent of its application, these do not exist in the context of a SORA based approach. Rather, a target reliability is derived, based on the SORA for each specific application to which the use of the UA is restricted.

The project ALAADy starts with the design of a UCA configuration for one ton of payload as well as possible scenarios for application. The project develops the safety critical components for a full system simulation and results in an economical and safety evaluation of such a system.

We aim at limiting the footprint of the flight routes to unpopulated areas and underneath the altitude of the remaining air traffic. By doing so, the restriction to the defined operation conditions can be ensured by emergency landing if a violation is immanent. For this purpose, conventional means of flight termination can be considered. However, as such a termination would involve financial loss and even more importantly hinder acceptance to such a system, inherent safety properties of the vehicle are considered. This inherent property refers to the possibility to passively perform an emergency landing with low impact energy and minimized damage to the system and its surrounding.

Furthermore, an avionics component, a so-called safety monitor, constantly supervises the state of the system in respect to the operational limitations. This safety monitor is in the chain of safety critical components ensuring the operation restrictions are not violated. This monitor triggers re-planning of the mission if a violation is expected to occur. As a last resort, the safety monitor also causes an emergency landing if all other contingency plans fail. It is the current understanding that with this safety approach, the reliability requirements of most of the other components of the UA can be relaxed, making for example the flight control and management system less complex and costly without having to reduce functionality.

The remainder of the paper is structured as follows: First, some general aspects on aircraft design are recalled and the unique differences to the approach used in this project are examined. Afterwards, the different work packages of the project are discussed. Finally, the concept for validation in a scalable simulation environment is sketched.

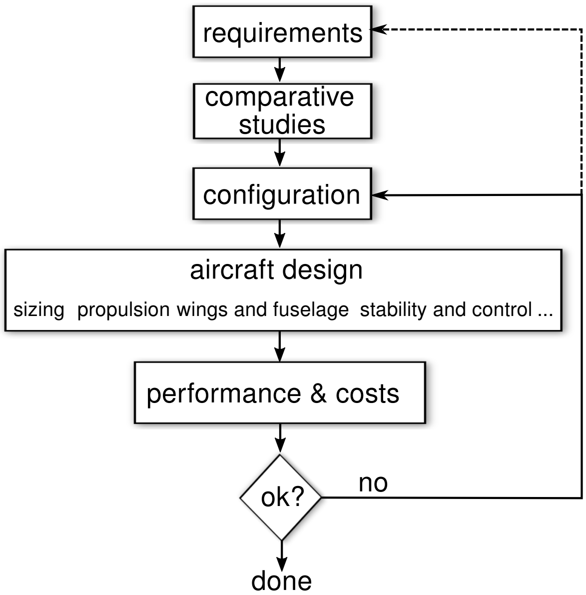

Figure 1: Simplified design process for manned aircraft

2. DESIGN METHODOLOGY

An iterative process for the design of a manned aircraft is well established. Figure 1 shows a simplified overview for the design process. It represents a procedure, which starts by defining requirements and finishes if the process does meet all the requirements. Based on [14] and [17] the design process can be sketched as follows.

Requirements, whether requested by a customer (e.g. an airline) or proposed by the manufacturer itself, as well as rules, e.g. from Certification Specification 25 (CS-25), are the baseline of the system design. Related to a civil transport airplane, a customer will quantitatively define fundamental properties like ([17]):

- Payload,
- Range,
- Take-off and landing distance,
- Cruise flight level and speed,
- Maximum size.

Often, existing configurations will be used to give an initial basic airplane design. Those comparative studies speed up the aircraft design and end up with one configuration or a set of configurations. Within the aircraft design process, different sub-components are combined. Figure 1 mentions some examples for those components including sizing, selection of propulsion, dimensions of the cabin and fuselage, and other sub-components.

Control surfaces, slats and flaps will affect the wing design and are fundamental for lift and roll control. Position of the center of gravity and moments of inertia determine the elevator and rudder construction. After their arrangement, stability and controllability are calculated.

Depending on the requirements, adaptation of the control surfaces and tail unit may be necessary. Subsequent to the definition of a landing gear, take-off weight, glide slope, and other properties are calculated. Moreover, flight performance is the base line for calculating operational costs. If either flight performance or operational costs are not consistent with the needs and expectations, changes of the planes' configuration or its size, will restart the aircraft design process as indicated in the flow of Figure 1.

Sometimes, changes to the requirements must also be taken into account. However, the structured design process sketched before will be supported by the CS-25/ FAR-25 and the Acceptable Means of Compliance (AMC). Those documents are subsequently split into a large number of sub-documents. Overall, the design is well established and is based on a solid fundamental set of rules.

In general, the design process of unmanned aircraft will be similar to manned aircraft. In contrast, however, due to the undefined safety targets in the operation centric risk context, we apply a slightly altered design process as shown in Figure 2. In general the flow of the process is equivalent. However, the performance criteria are now extended by the overall risks involved in operating the unmanned system. As a consequence, flight performance, overall costs and risks in a specific operation now determine whether the requirements are fulfilled. As a system design using the SORA approach has not yet been fully established and consequently unknowns remain, changes in the requirements are probable during this process.

Other aspects than the aircraft alone, namely the ground control station (GCS) and the data links between aircraft and GCS, influence the risks. Furthermore, the design of the software is added to the process in a very early stage. Development and certification of the software for aviation, is usually done according to the DO-178b/c [18]. A corresponding development process involves significant costs that scale with the design assurance level of the software components. In the project ALAADy, it is therefore investigated, if applying a new software architecture exploiting the potential of operation risk mitigation is likely to reduce the design costs (see next section).

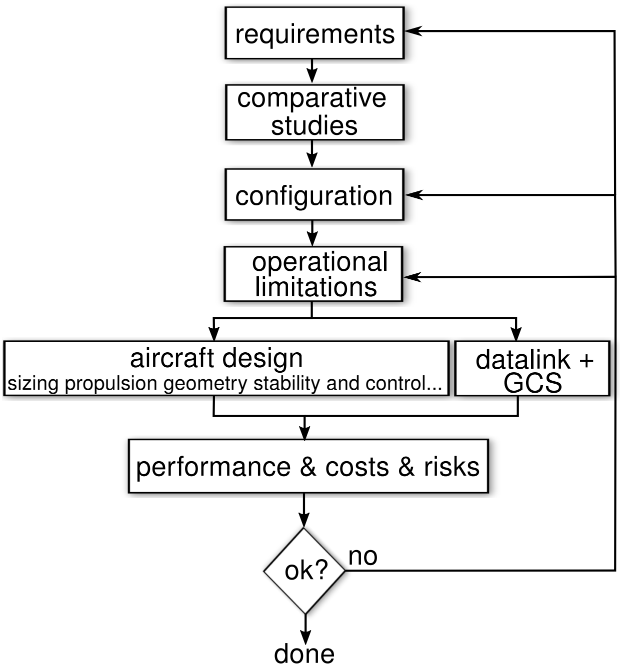

Figure 2: Simplified design process for the unmanned aircraft of ALAADy

If the risks are deemed to be unsatisfactory, two steps can be undertaken during the design loop of Figure 2. Either development effort can be invested into increasing reliability or alternatively, operational limitations can be introduced or increased ensuring safety of the overall system. These limitations can go beyond what is accepted for manned systems: Unmanned aircraft are often considered to be designed specifically for a certain kind of mission. The operation limits can go as far as limiting the unmanned aircraft to that specific mission.

3. GOALS OF THE PROJECT

In the context of the design process definition described in the previous section, there are four major questions the project ALAADy will provide contributions to:

Economic value: In many cases, the use of UA can be considered as a substitute for an existing solution on the market. The extent to which an UCA is a substitute or enabler of new delivery concepts, is unclear at this point. The circumstances in which the use of unmanned aircraft provide an economical benefit over logistic competitors has thus to be addressed within the project. A set of encouraging use-cases will therefore be discussed throughout all work packages.

Risk based approach: The boundaries of the EASA specific category has not yet been defined. One of the reasons is, that classification based on size or weight does not meet the manifold of possibilities of UA realizations. For this reason, ALAADy investigates if a SORA based approach is feasible for a system of this scale.

Setting/Environment: The environment of UA operation is currently in active development both from airspace integration and regulatory perspectives. It will be investigated how such an integration can be performed for the proposed UCA, how regulations affect the overall costs of such a system and how cooperative detect and avoid functionality can be achieved.

Feasibility: Different aspects of achievablility of the proposed UCA will be investigated. Of special interest for ALAADy are the algorithms and software required for safe operation. But also system architecture including on-board avionics, datalink and ground control station (GCS) are considered conceptually.

Figure 3 presents a view on the investigations of the project. At the beginning, a set of use-cases and aircraft (A/C) configuration is developed. The realization is conceived and algorithms dedicated to the new SORA concept are implemented. Based on the setting the UCA is operated in, the realization concept, both risks and overall costs are determined.

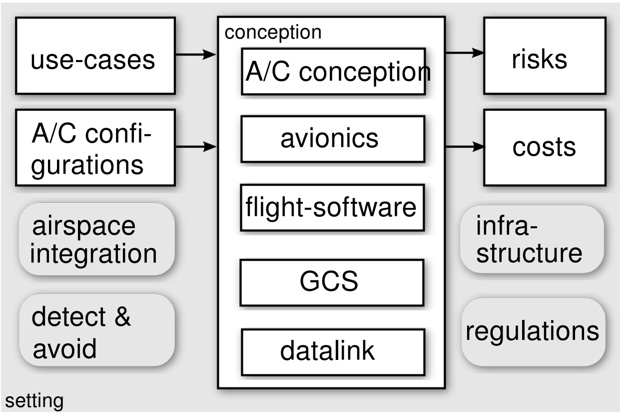

Figure 3: Overview on the aspects of the project

The use-cases are chosen to cover a sufficiently wide range of possible applications. For these applications market analyses are performed. Relevant companies that have been identified as possible stake holders like e.g. logistics providers or spare part distributors are interviewed. Furthermore, a survey is performed to asses the applicability of the use-cases focusing on experts on the capability of unmanned aircraft. Based on these results yield models are developed and the economical validity of a UCA with the above mentioned requirements is assessed.

Three different aircraft configurations are chosen by two fundamental characteristics. First, inherent safety properties are analyzed. This inherency refers to the aircraft by itself having a beneficial effect on the risk assessment—e.g. low impact energy or predetermined small areas covered by the gliding phase during an emergency landing. Second, the following basic flight performance requirements shall be fulfilled:

- range: 600 km
- cruise speed: 200 km/h
- payload: 1 t
- cargo space: $3{\cdot}1.3{\cdot}1.3\,\mathrm{m}^3 \approx 5\,\mathrm{m}^3$
- reduced runway length of < 400 m

A comparative study is performed to select appropriate configurations. See [10] for details on the performance part of the study and Figure 4 for an impression.

For the combinations of use-cases and configurations realization concepts of the UCA system are developed as shown in the middle block of Figure 3. This process starts by determining involved technological and economical requirements.

The aircraft itself is then assessed using a flight performance analysis including the question if innovative propulsion technologies would improve the different configurations. A structural analysis is also performed. By these means, a mechanical feasibility of the proposed aircraft is evaluated. Additionally, the inherent safety properties including possibilities for safe emergency landings are investigated.

The on-board hard- and software architecture is designed. The components of the on-board software are identified and critical ones are implemented for deeper analysis. We focus on algorithms contributing to the operation centric risk approach. One aspect is the motion planning toolchain, which shall consider the operation conditions and risks as well as motion safety.

Also part of the risk approach is a safety monitor. This monitor will observe the vehicle state and constantly compare it to the defined operation limitations. It is build on simple concepts and implemented using the least complexity possible. If these limitations are likely to be violated, the mission is aborted and counter measures are invoked. By doing so, achieving certification credits for this software module, which is ideally one of the very few highly critical ones, is expected to be facilitated.

An existing ground control station U-Fly of DLR [9] is adapted for the use-cases. Data link concepts are compared in the context of risk and a selection is proposed. It will be investigated whether continuously available and reliable datalinks for C2 (command and control) and flight termination are necessary to ensure the safe operation of the system. From another perspective, the same question is approached by investigating the interplay between the

(a) Fixed-wing configuration (b) Box-wing configuration (c) Gyroplane

Figure 4: Artistic depiction of the three chosen aircraft configurations

capabilities of the safety monitor and vehicle on the one hand and the requirements of the datalink on the other hand.

The setting of the UCA is considered during the project. Possibilities for airspace integration for very low level flights are discussed. Questions of technologies necessary for separation are equally considered as is the information management between the stakeholders. Closely related is the detect and avoid capability, which is one of the vigorously debated topics in the UA community enabling beyond-visual-line-of-sight (BVLOS) flights. For the very low level flight, adequate technologies are reviewed, a promising technology is selected and investigated in simulation together with the airspace integration concept.

Lastly, the aspect of infrastructure is important to review. Ideally, both dedicated as well as general airports should be served by the UCA. How the connection to a logistic chain could be achieved, effectively including possible ways of automation, needs to be explored.

All these different aspects define the unmanned cargo delivery system. All components are then analyzed in respect to involved risks in a SORA. The interaction between the significant risks found and the aspects of the UCA are analyzed. The goal of this process is to find a relationship between achievable safety and costs. This relationship enables optimizing the limitations of operation due to reduced reliability of the system on the one hand and the development costs to achieve an increased safety on the other hand.

4. VALIDATION: SCALABLE SIMULATION

To assess the performance of the UCA system beyond discussion and analysis of the component concepts by itself, a simulation is developed. Based on a configurable simulation environment for unmanned aircraft [2] example missions of all combinations of aircraft configurations and use-cases are simulated. These simulations are combined with an air traffic simulation [19] in order to be able to realistically populate the airspace.

There are two general goals of these simulations. First, a deeper understanding of integration aspects of the system shall be generated. While every solution to the low altitude cargo problem as described in the previous section is assessed by itself, many important aspects are revealed only if the different solutions have to work together to form a working system.

For instance, the aircraft configuration type will influences the economics (e.g. fuel consumption per distance traveled) as well as the complexity of the necessary safety architecture which drives the system acquisition cost. These are the kind of trade-offs that are being investigated. To this end, simulation trials will be performed investigating different aspects of the validation. The simulations also build the foundation for a possible future flight test implementation on a demonstrator vehicle. By this means, the general feasibility of the proposed system can eventually be assessed beyond the results of a pure concept study.

Second, the safety and costs of this concept are brought into focus. A system of this size has not yet been developed using an operation centric risk approach. Therefore, we strive to reach a well based statement whether this approach can be applied to unmanned cargo aircraft to this scale of payload or if it has a natural limit caused by facets analyzed within the project. We discuss the implications that certain safety targets have on the overall system costs.

To achieve these two goals, different simulation scenarios are developed. Using the configurable simulation framework presented in [2] the fidelity of the modules can be exchanged easily provided the interfaces remain unchanged. For some scenarios these levels of fidelity are easily determined. An example might be the safety of the path and trajectory planning under varying environmental conditions like weather.

Simplified, the requirements for the simulation modules are: The algorithms for planning itself have to be integrated into that simulation, and the aircraft simulation must be capable of adequately responding to weather conditions. In contrast, for some simulation scenarios, the level of fidelity is not a priori known. One example might be a certain critical hazardous air traffic situation which will follow the systematic risk assessment. Only if this scenario is identified, the level of fidelity of the required simulation can be concluded. In the latter example, it might be sufficient to statically represent the air traffic participants only on flight performance level without aerodynamic simulation thus significantly reducing the level of complexity.

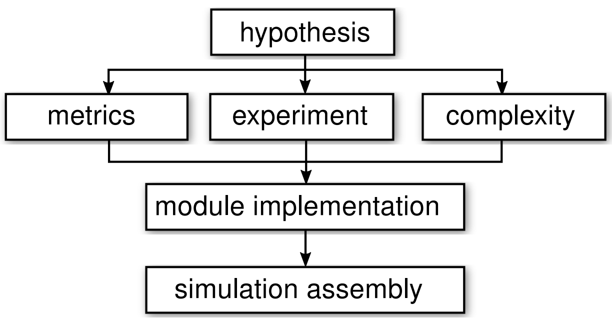

Figure 5: Simplified simulation experiment definition process

The general procedure of defining a simulation scenario follows Figure 5. The process is given by defining a hypothesis for the simulation first. Three components have to be defined to test this hypothesis: the experiment, metrics to measure the fulfillment of the hypothesis and lastly the modules' level of complexity. The result is a set of requirements on the simulation modules which will then be developed accordingly. Finally, the simulation assembly will be performed automatically by the framework. This process contrasts with choosing a simulation environment with maximal level of realism. Using a high fidelity simulation is best suited for investigative purposes. In contrast, for validation purposes an adequate implementation of least complexity may be selected to ease analyzing the relations between causes and observations as ambiguity in possible causes are avoided.

5. CONCLUSION

In this paper we provide an overview on the goals of the DLR project ALAADy started in the beginning of 2016 and ending 2018. In this project a low flying unmanned cargo aircraft for one ton of payload in very low altitudes is investigated. The specific operation risk approach suggested by EASA will be considered and analyzed. A goal of this project is to gain knowledge about the general feasibility of such a system as a first step.

Subsequently, the interplay between operation limitations and implied safety targets is analyzed. Intuitively, this can be understood as the balance between avoiding criticality of a risk by operation limits or by introducing a sufficiently reliable system design. However, the limits will have an impact on the use-cases that the unmanned cargo aircraft can be used for and increased safety targets have an impact on the development costs. Consequently, it is investigated whether a sweet spot between safety and economical revenue exists.

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Abbreviations

ALAADy	Automated Low Altitude Air Delivery
AMC	Acceptable Means of Compliance
BVLOS	Beyond Visual Line of Sight
CS-LURS	Certification Specification Light Unmanned Rotorcraft Systems
DARPA	Defense Advanced Research Projects Agency
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
EuroCAE	European Organisation for Civil Aviation Equipment
EASA	European Aviation Safety Agency
GCS	Ground Control Station
JARUS	Joint Authorities for Rulemaking on Unmanned Systems
RTCA	Radio Technical Commission for Aeronautics
SORA	Specific Operation Risk Assessment
TLR	Technology Readiness Levels
UA	Unmanned Aircraft
UCA	Unmanned Cargo Aircraft