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Development of Automatic Controllers and Piloting Aid Functions for Enhancement of UAV/OPV Autorotation Management

Laurent Binet Laurent.Binet@onera.fr Research Engineer ONERA Salon de Provence, France	Dr. Christian Brackbill¹ Lead Engineer CCDC AvMC AED Redstone Arsenal, AL, USA	David Quinn Branch Chief CCDC AvMC AED Redstone Arsenal, AL, USA
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INTRODUCTION

Unmanned Air Vehicles (UAV) and Optionally Piloted Vehicles (OPV) will play an increasingly important role in future military fleets. Rotary-wing autonomous systems are also studied for civilian applications. In all cases, one major limitation remains the control, guidance and management of automatic or pilot-assisted autorotation maneuvers. In the framework of the US/France Memorandum of Agreement for Cooperative Research on Helicopter Aeromechanics (PA AHFIR), ONERA and AvMC AED worked in close cooperation since 2011 on the potentiality of improving the flight safety and performance of manned helicopters when operated in autorotation. Specific controllers have been previously developed (Refs. 1, 2) in order to assess UAV/OPV autorotation performance metrics.

One of the main objectives of this cooperation is the development and evaluation (through off-line or piloted simulations) of automatic controller concepts for UAVs and the study of their transfer to an OPV configuration with their partial or complete use in piloting aids. The paper will present the latest developments performed in this study, tackling the overall autorotation maneuver issues: the autorotation entry, the selection and guidance towards a potential landing zone and the final flare and landing maneuver (Fig. 1). Major developments have been carried out and will be detailed:

- Landing Zone selection and guidance/navigation towards the selected zone; and
- Integration of a purpose-built controller for final approach, flare and landing (adapted from Ref. 3).

Drive train monitoring and the capability of engine failure recognition by an automatic system is part of the overall problem and previous work at AvMC AED (Ref. 4) has focused on the subject. In addition, a “direct” rotor RPM control through the collective has been designed and tested for manned helicopters, and is presented in this paper.

ONERA and AvMC AED share common simulation tools, based on FlightLab® flight mechanic code, an OH-6A helicopter model (Ref. 5), and MATLAB/SIMULINK for (A)FCS models. Automated autorotation management has been an active research topic for many years, and the full paper will include additional discussion of other approaches available in the literature.

LANDING ZONE SELECTION ALGORITHMS

ONERA has developed specific algorithms, enabling the selection of reachable landing (or crash) zone (noted LZ hereafter and represented in Fig. 1) once the engine failure has occurred. If these algorithms are mandatory for UAV, to control the helicopter as much as possible towards a safe area, they could also be used in OPV to provide to the pilot a selection of potential LZ and dedicated piloting aids.

These algorithms are based on the hypothesis that a precise and detailed terrain database is available onboard as shown in Fig. 2. Pre-defined LZ (blue stars) are defined in this database, in terms of position but also with different features, such as if the LZ is a runway (green arrows) or if it requires a prescribed heading (red arrows) to land on it (narrow field). In addition, the terrain database includes the areas to avoid (i.e. towns – red zones) as well as the terrain elevation. The trajectory generation, from the helicopter position at the engine failure to the LZ location, is based on Dubins curves (Ref. 6) and is part of the selection logics. Prioritization logics have been developed in order to select the “best” reachable LZ in case of emergency. The trajectory (green line from helicopter to the selected LZ) is computed and used by the guidance controller. The paper will describe these logics and provide examples such as in Fig. 2.

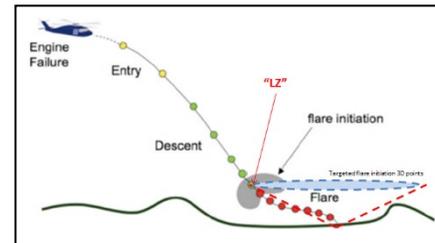


Fig. 1. Complete Autorotation Management Task

¹ Corresponding Author

As pilots take into account the wind when choosing the landing zone, wind considerations have been introduced in the selection algorithms based on meetings and recommendations of pilots. If an onboard wind estimator would be required, this development is out of the scope of this study and it supposed that the magnitude and direction of the wind is known by the system. The paper will describe how wind conditions are taken into account and their impact on the selection of the LZ through multiple examples.

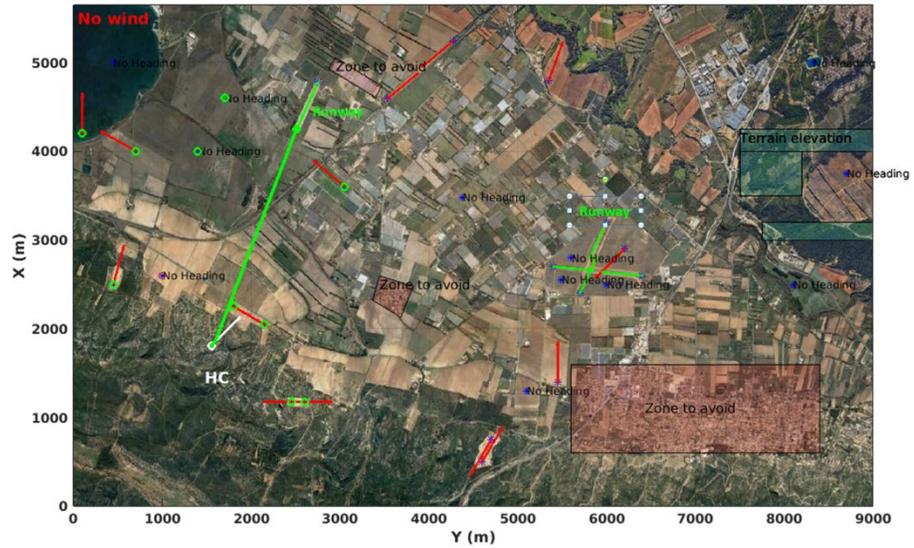


Fig. 2. Example of Landing Zone selection

AUTOMATIC GUIDANCE TOWARDS SELECTED LZ

Based on the LZ selection algorithms, an automatic controller has been setup to guide the UAV towards the LZ. At the engine failure, the rotor RPM is regulated and adapted to the selected LZ while the Indicated Airspeed (IAS) is controlled to track the required glide slope. Once the autorotation is stabilized, the controller is dedicated to:

- An IAS regulation to track required glide slope +
- A rotor RPM control for slight slope adjustments +
- A heading/roll control for guidance to selected LZ + final adjustment if a specific heading is required

The paper will describe the automatic entry and guidance controller in more detail, and present results demonstrating that this controller is able to pilot the UAV from the engine failure to a selected LZ as seen in Fig. 3.

Here, the engine failure occurs at 1s. The controller immediately manages the rotor RPM and guides the helicopter toward the selected LZ by performing a left turn and decelerating from 60 kts to around 54 kts. The controller manage the glide slope by slight adjustments of the airspeed (U) and RPM. Before the flare initiation point, the heading is changed to correspond to the prescribed one.

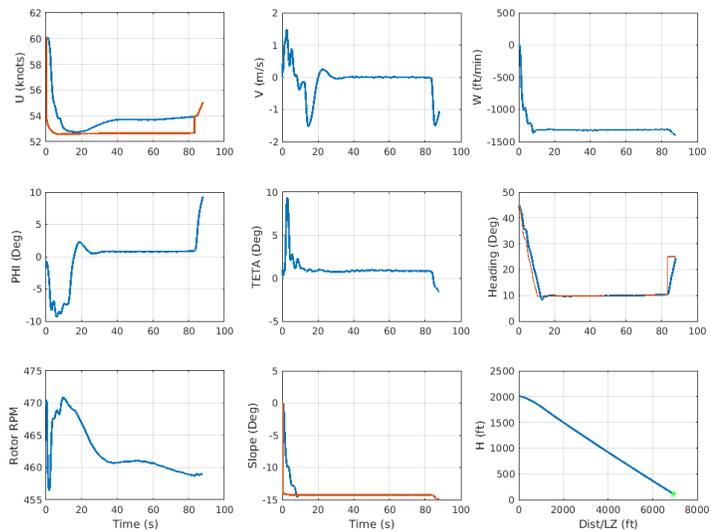


Fig. 3. Guidance algorithm development

OPV PILOTING AID FUNCTIONS

While an automatic controller has been developed for an unmanned machine, discussions and exchanges helped us to define the most relevant piloting aids expected by pilots. Thus, as the time to react at the engine failure is very short, the piloting aids for autorotation entry would be similar, as automatic, to the one used in the UAV controller:

- Automatic rotor RPM regulation
- Automatic Airspeed regulation, potentially adapting the current airspeed to an optimal one
- Attitude (roll, heading) stabilization at engine failure
- Proposition of 3 LZ

For the stabilized phase, as the main hypothesis is that the pilot has to remain in the control and decision loop, specific piloting aids would be useful:

- Update of 3 proposed LZ + useful flight parameters to reach them + show the maximal achievable range
- Direct rotor RPM control through collective

These specific aids will be discussed in the paper, and more especially the direct rotor RPM control through collective which has been developed. In Fig. 4 it can be seen the different flight phases before and after an engine failure and the corresponding behavior of the rotor RPM controller. Thus, in Phase:

- A: Before engine failure; the rotor RPM is maintained to its nominal value (470) by the “classic” regulation, even as the pilot pulls on the collective
- B: Engine failure; the controller automatically switches on, recovers the nominal rotor RPM (470)
- C: Stabilized descent; the pilot can directly control the rotor RPM through the collective (full down leads to the maximal limit of 500 RPM, full pulled, to the minimal limit of 375 RPM)
- D: Flare/landing maneuvers; below a prescribed height (here 120 ft), the controller automatically switches to the classical blade pitch control.

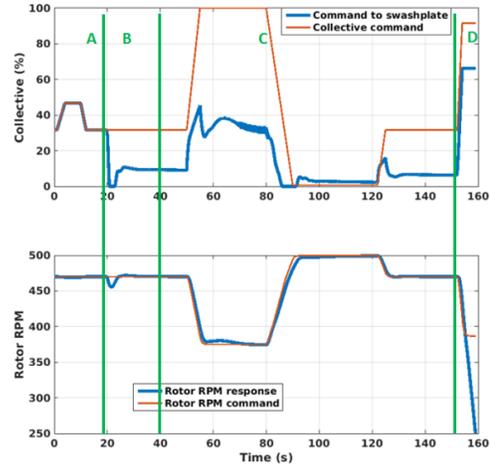


Fig. 4. Direct rotor RPM control through collective

FLARE/LANDING CONTROLLER AND FLARE MANEUVER PARAMETER ANALYSIS

The flare/landing controller here has been adapted from previous research at Texas A&M and Georgia Tech (Ref. 3). This controller applies specifically to the final approach, flare, and landing of the helicopter in autorotation. As such, it only controls collective and longitudinal cyclic. Additional control for the lateral and directional axes must be provided within the simulation. The basic control strategy is to manage the RPM and airspeed/pitch attitude during steady descent phase, based on pre-selected targets for both the steady descent and touchdown airspeeds. The controller uses fuzzy logic based on a calculated “time-to-impact” (TTI) to determine when to begin the flare, landing, and touchdown phases. During these latter phases, the collective (vertical) axis switches to a tau-based controller (h/\dot{h} where h is the distance from the ground), scaled by the available energy, while the longitudinal axis uses pitch attitude to continue to target the pre-selected touchdown airspeed.

This controller has been implemented in the current simulation framework, coupling a Simulink model to the OH-6A FlightLab® model. The simulation must, again, have a separate control strategy for lateral/directional control in the final autorotation phases. In this case, once the aircraft is on final approach, the lateral axis uses an attitude hold PID (zero roll angle) while the directional axis uses a heading-hold PID (desired final heading). These two independent controllers make use of the TTI parameter to switch to zero-roll-rate and zero-yaw-rate control just before touchdown. Fig. 5 shows a simplified block diagram for this controller. See Fig. 6 for an example of the fuzzy logic phase transition and TTI for the baseline case.

The baseline case shown in Fig. 6 is the OH-6A simulation case that was used to initially tune the flare/landing controller. The model is trimmed at an altitude of 700 ft, 60 kts indicated airspeed, and 2600 lbs gross weight. The autorotation RPM target is set to 100% during the descent and the target airspeed is maintained at 60 kts. The maximum flare pitch attitude is set to 12 degrees, and the touchdown airspeed target is set to 12 kts. Other controller gains and internal settings will be listed in the paper, and are

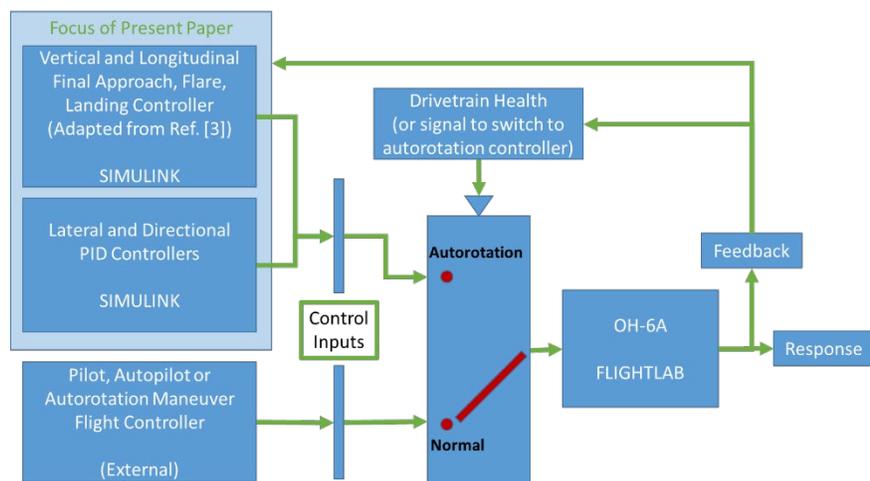


Fig. 5. Simplified block diagram of autorotation landing controller implementation

discussed in detail in Ref. 3.

Various controller parametric studies have been conducted to examine the robustness of the controller during the landing phase, and to determine the range of acceptable target flare entry parameters to provide to the previously discussed LZ selection and guidance algorithms. One such parametric study example is shown here in Fig. 7. In this case, the max flare pitch attitude target is varied from the baseline case. Three cases are shown: 12 (baseline), 7, and 17 degrees. The figure presents the x-y-z body velocities (v), the altitude (H) and ground track (x, y), the body attitudes and rates ($\phi, \theta, \psi, P, Q, R$), sideslip (β), rotor speed (NR), climb rate, and the four control inputs. Each simulation begins from level trimmed flight. After a brief delay, the clutch is disengaged to simulate a drive train failure, and after another brief delay the autorotation controller is activated. Note that upon touchdown the simulation is continued for 10 seconds using the default ground conditions in FlightLab®. The intent is to demonstrate realistic simulated landing conditions to the best extent possible. As expected, there are significant differences for v_x and θ during the flare phase, with very little difference during other phases. Notably, the highest flare pitch attitude does require a higher collective pull (and larger RPM reduction) because of the significantly reduced touchdown airspeed. There is also a 10 degree heading change at touchdown, resulting from a combination of higher main rotor torque (from the collective pull) and larger off-axis (roll) response causing touchdown to occur initially on one landing skid. This may represent a limiting case for this particular aircraft and controller combination. Additional parametric study results, including gross weight, autorotation RPM, and autorotation airspeed variations will be presented in the full paper.

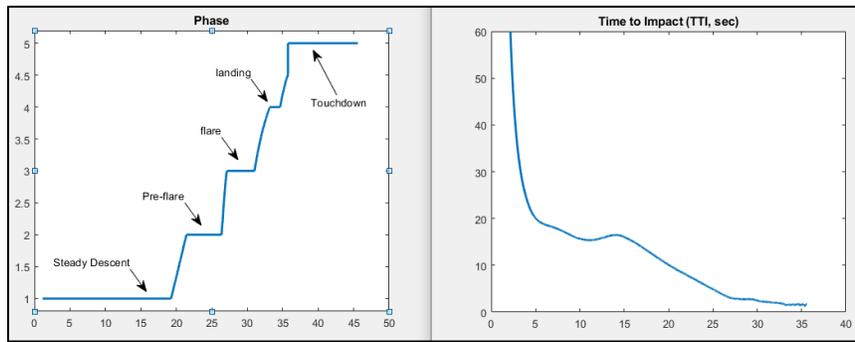


Fig. 6. Example of controller Phase and Time to Impact (TTI) parameters, baseline case

is varied from the baseline case. Three cases are shown: 12 (baseline), 7, and 17 degrees. The figure presents the x-y-z body velocities (v), the altitude (H) and ground track (x, y), the body attitudes and rates ($\phi, \theta, \psi, P, Q, R$), sideslip (β), rotor speed (NR), climb rate, and the four control inputs. Each simulation begins from level trimmed flight. After a brief delay, the clutch is disengaged to simulate a drive train failure, and after another brief delay the autorotation controller is activated. Note that upon touchdown the simulation is continued for 10 seconds using the default ground conditions in FlightLab®. The intent is to demonstrate realistic simulated landing conditions to the best extent possible. As expected, there are significant differences for v_x and θ during the flare phase, with very little difference during other phases. Notably, the highest flare pitch attitude does require a higher collective pull (and larger RPM reduction) because of the significantly reduced touchdown airspeed. There is also a 10 degree heading change at touchdown, resulting from a combination of higher main rotor torque (from the collective pull) and larger off-axis (roll) response causing touchdown to occur initially on one landing skid. This may represent a limiting case for this particular aircraft and controller combination. Additional parametric study results, including gross weight, autorotation RPM, and autorotation airspeed variations will be presented in the full paper.

ADDITIONAL TOPICS TO BE DISCUSSED IN THE FULL PAPER

Communications between the various phase controllers: The parameter TTI can, potentially, be used to feedback information to the pilot and the landing zone selection algorithms. The LZ selection and guidance algorithm can, of course, also supply information to the final landing controller in order to allow for a smooth control system hand-off between guidance/maneuver phase and the final approach and landing phase. The guidance and LZ selection algorithms also require acceptable flare entry targets for parameters such as airspeed and descent rate. These can potentially be made available by pre-running the flare-landing controller for a known acceptable range of target values. It is likely beyond the scope of the present study, but flare/landing controller entry targets may also include changes related to the landing surface. For example, a water landing would “force” a zero forward speed landing and a tree-top landing would set an artificial “floor” at the tree-top level, as well as set the forward speed target to zero. All of these parameters require interaction between the various controller phases and, for the OPV, potential interaction with the pilot.

Comparisons of flare/landing phase controllers: The Ref. 3 controller adapted for the present study has been developed specifically for the autorotation landing phase. It has been used extensively in simulation for AH-1, UH-60, and smaller RC helicopters. Previously, ONERA also developed controllers specifically for this OH-6A study (Ref. 2). The full paper will compare these two flare/landing controllers. The paper will also demonstrate, for selected points, an approach to assessing controllers against the H-V curve for the OH-6A.

Final results: The stated purpose of this task is twofold: first, to propose a system that can both improve and automate the emergency autorotation landing task for UAVs, as well as provide piloting aids for OPVs; second, to build a desktop simulation environment with high enough fidelity to test these types of controllers prior to implementing them on board a UAV or a manned simulator.

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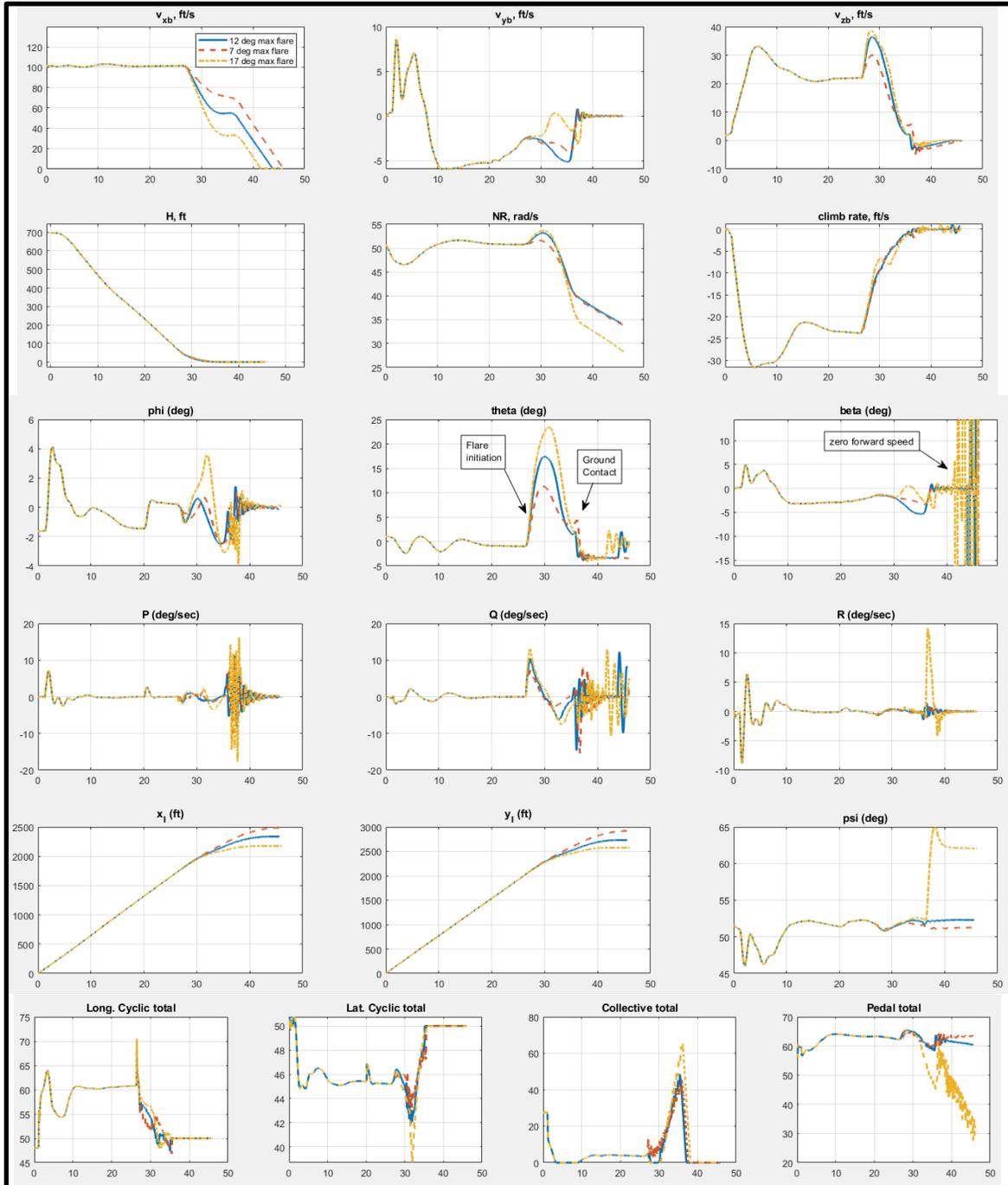


Fig. 7 Autorotation landing controller showing the effect of varying the maximum flare pitch attitude