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STRATEGIES FOR MANUAL LANDING OF REMOTELY PILOTED AIRPLANES WITH LARGE TIME DELAY

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Abstract

Remotely piloted aircraft systems (RPAS), when operated beyond visual line of sight, are usually affected by considerable signal transmission time delays. It is known that time delays reduce the stability margins of a control loop and can cause instability, also when the loop is closed by a human operator. Hence, time delays are avoided in (manual) flight control. For RPAS, this means that landing as a high precision tracking task is usually accomplished either by a local pilot who is confronted with only negligible time delay, or by an automatic landing system. While the first strategy requires a local pilot, the second requires an intact guidance and navigation infrastructure. This paper presents and compares alternative strategies for remotely controlled landing through communication links with round trip time delays as high as several seconds. The analyses indicate that higher-level maneuver demand systems and open-loop piloting techniques may provide adequate handling qualities at the cost of potentially long landing distances or increased vehicle weight.

1 Introduction

Although the very critical landing phase of an RPAS can be safely accomplished by automated systems or by a local pilot, remote manual landing through large time delays may be necessary in some situations. For instance, it may not be possible to deploy an operator and a ground control station (GCS) at the landing site, the landing site may not offer guidance systems like an instrument landing system (ILS), or the RPAS may not possess adequate onboard sensors for automated landing. Moreover, failure of ground-based guidance, GCS or onboard sensors, or the inability to hand over control from remote to local pilot may result in a situation where remote manual landing is required.

Long-distance communication links between GCS and RPAS usually employ one or more satellites or ground-based relay stations. The long distance itself as well as datalink electronics, encryption, compression and other computations introduce a high amount of latency. For a geostationary satellite relay, a minimum round-trip time delay of 674.0 ms is estimated in [1]. Other sources report even higher values up to 8 s [2-4].

The negative effects of time delays in control loops are known. At best, they slightly reduce the phase margin and at worst, they destabilize the system. In manual control tasks, time delays have found to cause regression of the pilot-vehicle open-loop bandwidth [5]. At the same time, pilots generate excessive lead and need to devote considerable attention to the task to do so. This corresponds to a high mental workload. As a result, a characteristic operator behavior occurs, where abrupt, pulse-like control inputs are made instead of smooth and continuous inceptor movements. This behavior, which can be seen as an attempt to reduce workload [6, 7], is often combined with the so-called move-and-wait strategy [8, 9] where the delayed reaction of the system is observed after each brief control input.

It is quite obvious that landing, or any other high-precision, high-bandwidth task, is extremely challenging under these adverse circumstances. The aim of this paper is therefore to identify suitable piloting techniques and RPAS flight control system characteristics that facilitate the landing task. Although the performance of flight control with negligible delays cannot be matched, a slight handling improvement may already reduce the large number of RPAS accidents attributable to human error [10].

2 Piloting Techniques

It shall be assumed that during the landing approach, any RPAS follows a prescribed trajectory, with a ground track along the extended centerline of the runway or the designated landing area and a glide slope of approximately 3°. The landing is then characterized by the actions of the pilot starting several seconds before touchdown until the RPAS comes to a halt on the ground. This section first describes four prototypical landing techniques employed today in different operational settings. Then, two crosswind landing techniques are compared and finally, their suitability of each landing technique for RPAS with large time delays is discussed.

2.1 Prototypical Landing Techniques

In manned airplane flight, several piloting techniques exist for the landing phase, each adapted to the requirements of a different operational environment [11, 12]. Starting from straight flight along a defined glide slope, the aim of the landing maneuver is to produce a suitable touch down. This may mean that the vertical speed is reduced, or that the airplane is brought to a specific attitude, or both. One part of the landing is therefore the flare maneuver, where the nose is raised and the flight path thereby made shallower. How pronounced this flare maneuver is differs between the following prototypical landing techniques.

In light, tricycle-gear airplanes, pilots usually flare high and hold the airplane off the ground as long as possible while decelerating. Ideally, the airplane touches the ground when stalling. Thus, bouncing off the ground is avoided. In airplanes with conventional landing gear, the nose is raised only so much as to attain an attitude where all three wheels can touch down simultaneously to make a three-point landing. By design, this attitude is approximately the same attitude as in level flight stall. This technique of a well-pronounced flare with precision flight path and attitude control requires a rather high bandwidth, especially because light airplanes or RPAS with low wing loading are strongly affected by wind and turbulence during this prolonged maneuver.

Larger airplanes that are equipped with spoilers are normally landed with an equally pronounced round-out, but pilots allow the plane to touch down as soon as vertical speed is sufficiently reduced. Bouncing is subsequently prevented by spoiler deployment. It has been shown that the trajectory of the pilot station during the round-out of such landings can be described either by a circular arc, by an exponential function, or by a combination of both [13]. A similar case is the wheel landing in an airplane with conventional landing gear, where main-wheel touchdown occurs right at the end of the round-out. At this point, the inceptor needs to be moved from a nose-up position to a nose-down position to hold the airplane on the ground. In both cases, the airplane touches down earlier, the maneuver is shorter and a prolonged float is avoided. The time the airplane is affected by wind and turbulence is reduced. Nonetheless, the combined flight path and attitude tracking task requires a high pilot-vehicle bandwidth.

There are two prototypical landing techniques that do not comprise a flare maneuver. An aircraft carrier landing is the first example. It is an extremely demanding task that requires precision attitude and flight path control and therefore does not constitute a good reference for the present problem of remote landing with large time delays. The second example, on the other hand, is the open-loop strategy of landing a seaplane on glassy water. Glassy water is mirror-like and does not provide sufficient visual cues for depth perception, thus effectively preventing any closed-loop flare maneuver. The technique consists in adopting a given pitch and power setting above land, where visual cues are still sufficient to determine altitude, and letting the airplane descend along the resulting flight path until it contacts the water surface. This constant-vertical-speed technique is also sometimes employed for automated landing of unmanned vehicles.

Regardless of what landing technique is employed until touchdown, pilots need to decelerate during the landing roll while maintaining directional control. This can be a challenging high-bandwidth task in aircraft that are directionally unstable, as for instance tailwheel airplanes.

2.2 Crosswind Landing Techniques

If a landing with some crosswind component is required, the aim is to touch down without drift, in a nearly wings-level attitude and aligned with the landing strip. In such a crosswind landing situation, pilots normally rely on one of two piloting techniques: the crab technique or the wing-low (sideslip) technique.

The crab technique consists in drifting down the glideslope with the wings level and the airplane heading offset from the runway heading, so that the resulting ground track is along the extended runway centerline. Just prior to touchdown, i.e., during flare if applicable, the heading offset is canceled while maintaining wings-level attitude by coordinated and positive application of rudder and aileron inputs. Touchdown has to occur before significant drift develops.

During an approach with the sideslip technique, on the other hand, both the ground track and the airplane heading are aligned with the landing strip. As a result, the airplane needs to slip with the upwind wing low. Touchdown occurs still slightly banked with the upwind part of the main landing gear first.

The crab technique is commonly used in large transport aircraft and requires a sudden and precise application of control inputs prior to touchdown, whereas the sideslip technique is recommended for light airplanes and requires constant corrections of drift and heading throughout the approach until touchdown.

2.3 Suitability of Landing Techniques

The choice of a suitable landing technique for a given RPAS depends on multiple factors, such as the size and wing loading of the vehicle, the operational context and possibly the control system type (cf. section 4). This section more generally analyzes the previously described prototypical landing techniques with respect to their suitability for remote landing with large time delays.

Considering that the pilot-vehicle bandwidth attainable is greatly reduced by the presence of time delays, a landing technique should be chosen that only requires minimal and gradual control activity by the pilot. For instance, a prolonged closed-loop flare maneuver during remote landing with large time delays is likely to produce pilot induced oscillations and, as a result, an unsafe landing or a crash.

The constant-vertical-speed landing technique or a landing without flare, on the other hand, are much more suitable for RPAS operations with time delay, because they can be flown basically open-loop. It must be noted, however, that pilots would not fly purely open-loop, even with considerable signal transmission latency. Once they notice that the airplane is too high or too low during the maneuver, they can make corrective inputs. These corrective inputs may be done open-loop using the move-and-wait strategy, with a subsequent assessment of the delayed airplane reaction. As a consequence, a hybrid landing technique is thinkable as well, where the flight path is made shallower and shallower in multiple move-and-wait iterations until touchdown.

For crosswind landings of RPAS with time delay, the sideslip technique is preferable since it does not require sudden control inputs prior to touchdown. However, the control system type and the command variables (cf. section 4) would have to enable a steady sideslip until touchdown. If this is not the case, it may be necessary to make a crabbed approach and perform a high-bandwidth de-crab maneuver prior to touchdown which may very well trigger pilot-vehicle instability. If the landing is performed without flare and vertical speed thus is constant before touchdown, it is easier for the pilot to judge the right moment for the de-crab maneuver in the presence of large time delays and he is relieved from making both lateral and longitudinal control inputs at the same time.

3 Implications on Landing Distance

The minimum attainable landing distance is not only determined by environmental conditions (air density, wind, landing site surface conditions, etc.) and the airplane's means of deceleration (wheel brakes, air brakes, thrust reversers, etc.), but also to a large part by the piloting strategy employed for the landing task. Therefore, operational constraints influence the suitability of certain landing techniques and vice versa.

Fig. 1 shows a sketch of the landing trajectories resulting from the four prototypical landing techniques described above, namely landing without flare (case A), with flare (case B), with flare and float (case C) and, finally, with constant vertical speed (case D). It can be seen that, for geometrical reasons, the distance to touchdown d_{td}, measured from the landing strip's threshold, increases from case A to case B and to case D. If the glide slope is inclined at an angle of φ_{gs} with respect to the horizontal plane, the touchdown distance without flare is:

$$d_{td,A} = \frac{H_t}{\tan(\varphi_{gs})} \tag{1}$$

The touchdown distance with flare as in case B is, assuming that the round-out flare is a circular arc that starts at a height H_1 and ends on the ground:

$$d_{td,B} = \frac{H_1 \sin(\varphi_{gs})}{1-\cos(\varphi_{gs})} + \frac{H_t - H_1}{\tan(\varphi_{gs})} \tag{2}$$

If the flare is followed by a floating phase until stall occurs, the touchdown distance is increased accordingly:

$$d_{td,C} = d_{td,B} + d_{fl} \tag{3}$$

The floating distance d_{fl} can be calculated as follows, where $\dot{V}_{avg}$ is the average change in speed during the float:

$$d_{fl} = V_{app} \cdot t_{fl} + \frac{1}{2}\dot{V}_{avg} \cdot t_{fl}^2 \tag{4}$$

The duration of the floating phase t_{fl} in turn can be written as follows:

$$t_{fl} = \frac{V_S - V_{app}}{\dot{V}_{avg}} \tag{5}$$

Assuming zero thrust, the average change in speed during the float $\dot{V}_{avg}$ results from the drag equation, with air density ρ, average drag coefficient $C_{D,avg}$, mass m and average speed $V_{avg} = (V_{app} + V_S)/2$.

$$\dot{V}_{avg} = \frac{-\rho \cdot V_{avg}^2 \cdot C_{D,avg}}{2 \cdot m} \tag{6}$$

Finally, if as in case D the glide slope is made shallower at a certain height H_2 above the landing site and a descent with constant vertical speed and constant landing angle φ_{ldg} ensues, touchdown occurs after the following distance:

$$d_{td,D} = \frac{H_2}{\tan(\varphi_{ldg})} + \frac{H_t - H_2}{\tan(\varphi_{gs})} \tag{7}$$

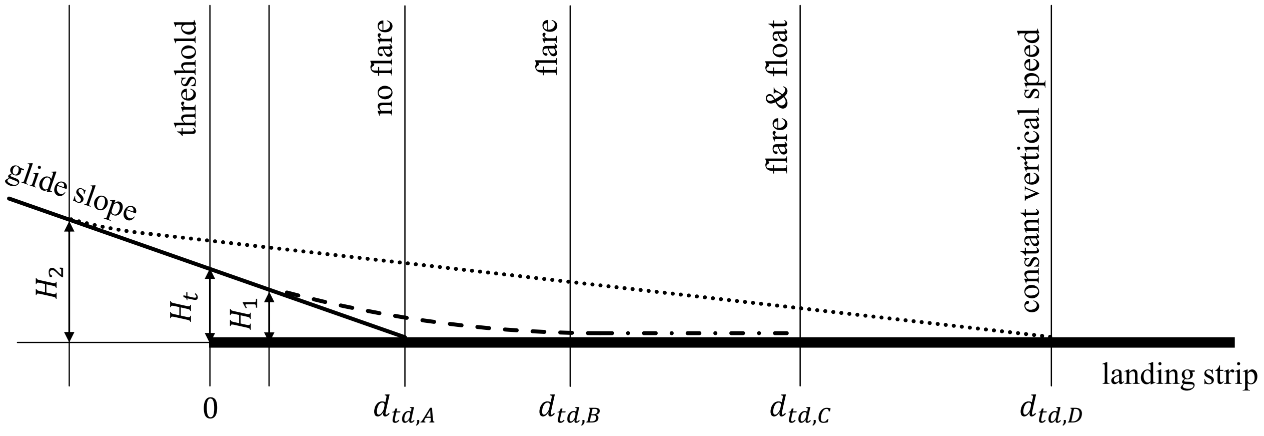

Fig. 1. Sketch of touchdown points with different piloting strategies

In all cases A through D, the distance of the landing roll following a touchdown with speed V_{td} can be calculated in a simplified manner as follows, with the gravitational acceleration g and the braking coefficient μ_{br}:

$$d_{lr} = \frac{V_{td}^2}{2 \cdot g \cdot \mu_{br}} \tag{8}$$

It can be assumed that in cases A, B and D, the final approach airspeed V_{app} is maintained until touchdown. In case C, on the other hand, touchdown occurs with minimum speed, i.e., stall speed V_S. Hence, roll-out distance is the same in cases A, B and D, but smaller in case C. Decelerating on the ground, however, is more efficient than bleeding off speed in a float, even when braking action is poor. Therefore:

$$d_{td,B} + d_{lr,B} < d_{td,C} + d_{lr,C} \tag{9}$$

As indicated above, the landing distance is indeed not only influenced by the landing technique, but also by air density, aircraft mass and braking action. Hence, a numerical analysis would have to be based on many assumptions, which would greatly compromise the significance of the results and is therefore left out here. Instead, the impact of parameter variations is analyzed.

Say, for instance, that the height above threshold H_t nominally is 15 m. In a real landing approach, however, the airplane may come in a little higher or lower, depending on environmental disturbances, pilot skill and other factors. Assuming that H_t is a random variable with a mean of 15 m and a certain variance $\sigma_{H_t}^2$, the resulting variations in touchdown distance can be analyzed using equations (1), (2), (3) and (7). In each case A through D, the variance of the touchdown distance is $\sigma_{H_t}^2 / \tan(\varphi_{gs})$.

The charm of a landing without flare (case A) is that no maneuver is required prior to touchdown and that, as a result, touchdown distance is only affected by variations of H_t and φ_{gs}. In cases B and C, on the other hand, the pilot needs to initiate the flare maneuver at a certain height H_1. If transition to flare occurs with a given variance $\sigma_{H_1}^2$, the touchdown distance varies with $\sigma_{H_1}^2 / \sin(\varphi_{gs})$. This variation adds to the effect of variations in H_t and φ_{gs}. Similarly, a transition to a shallower landing angle needs to be performed in case D. If here, H_2 varies with $\sigma_{H_2}^2$, the resulting touchdown distance exhibits a variance of $\sigma_{H_2}^2 (1/\tan(\varphi_{ldg}) - 1/\tan(\varphi_{gs}))$. When compared with the effect of variations in H_t or in H_1, this effect can become quite pronounced if $\varphi_{ldg} < \varphi_{gs}/2$.

Summing up, it can be said that landing distance is shortest without flare (case A), longer with a flare (case B) and still longer with a flare and a float (case C). Depending on φ_{ldg} or, in other words, the permissible vertical speed at touchdown, landing distance is potentially longest with the constant-vertical-speed strategy (case D). Variations in landing distance are smaller in case A than in all other cases. In case D, landing distance and variations thereof need to be traded off against vertical speed at touchdown.

4 RPAS Design Considerations

RPAS flight control systems are digital by nature and can therefore be implemented as maneuver demand systems in a straightforward manner, depending on the sensors installed. A first step in the layout of a maneuver demand system is the choice of suitable command variables.

As time delays reduce the maximum attainable pilot-vehicle bandwidth, the controlled variables should vary on larger time scales. Thus, high-frequency control, including disturbance rejection, is done by the on-board algorithms. Since time scales increase from rotational dynamics to translational dynamics in airplane flight, translational or flight path command variables can be considered more suitable than rotational or attitude command variables.

The choice of command variables, however, is also intrinsically tied to the piloting technique employed. For instance, while pilots may perform flight path control during the landing approach, precise attitude control may constitute a parallel objective during landing and touchdown. In this case, the flight control system must provide attitude control. A possible solution would be to blend between command variables. In the longitudinal motion, for example, the approach phase could be accomplished with a $\dot{\gamma}$ (flight path climb angle rate) command system, which requires only few control inputs [14], whereas the control algorithms could blend to a q (pitch rate) command system prior to touchdown.

Another trade-off in the choice of command variables has to be made in terms of sensor suite requirements or, in other words, in the level of automation. The higher the level of onboard automation is, the less critical are time delays in remote control. At the same time, a more automated system is either more vulnerable to sensor failure, or requires a redundant set of sensors, adding weight and complexity, to mitigate this vulnerability. In this regard, a q command system may be easier to implement and operate than a $\dot{\gamma}$ command system.

Another aspect to consider in RPAS flight control system design is the pulse-like operator behavior observed when controlling systems with large time delays. It may indeed be beneficial to implement an on-off control system tailored to this behavior to reduce mental workload. A more detailed description of this approach can be found in [7].

Section 2.3 identified those piloting techniques without flare as most suitable for RPAS landings with large time delay, since they can be flown more open-loop. These techniques, however, would require a reinforced landing gear and possibly also spoilers, both of which would increase the weight of the RPAS. As section 3 indicates, a trade-off can be made between landing distance and vertical speed upon touchdown or, in other words, kinetic energy that needs to be absorbed by the landing gear. Assuming $H_2 = H_t$ and small angles φ_{ldg}, a reduction of the vertical kinetic energy upon touchdown to 25% of its original value can be achieved by landing with $\varphi_{ldg}/2$, which in turn doubles the distance to touchdown and magnifies the effect of variations of H_2.

On the ground, RPAS should exhibit positive directional stability if they have to be controlled through large signal transmission latencies. A turn rate command / heading hold controller would even further improve ground handling.

5 Conclusions and Outlook

A flight control system suitable for remote manual landing with large time delays could provide higher-level flight path control at least during approach and possibly also until touchdown. Lower levels of automation increase pilot workload and system availability at the same time.

Those landing techniques without flare, but with constant vertical speed were identified as most suitable for RPAS landing through large time delays, as they allow pilots to generally perform open-loop control with occasional corrective inputs. This proposed strategy requires either a more reinforced landing gear or even spoilers, thus adding some weight and complexity, or a long landing strip that accommodates the increased landing distance.

Although a rather constant crosswind component could be acceptable, remote landing with large time delays is highly challenging in variable winds and strong turbulence, due to the low pilot-vehicle bandwidth. The only mitigation here would be to increase RPAS onboard automation.

A more detailed insight into the suitability of different flight controller configurations and piloting strategies could be gained with simulator experiments. Additionally, visual aids such as predictor displays, could be implemented for the present problem and their effectiveness investigated.

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